Users' Manual for Computer Code DYSEAL
Dynamic Response of Seals

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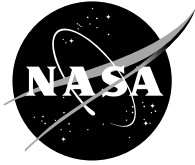
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1.0 INTRODUCTION

Dynamic response of seal rings to rotor motions is an important consideration in seal design. For contact seals, dynamic motions can impose significant increases in interfacial forces, resulting in high wear and reduction in useful life. For fluid film seals, the rotor excursions are generally greater than the film thickness, and if the seal ring does not track, contact and failure may occur. The computer code described in this manual can determine the tracking capability of fluid film seals and can be used for parametric geometric variations to find acceptable configurations.

The type of seals that can be analyzed are depicted in Figures 1* through 3. Figure 1 shows a stationary seal ring and a rotating mating ring. The secondary seal is a piston ring with radial pressure loading on the OD. The shaft or rotor can be given five degrees of freedom, consisting of three translations (x, y, and z) and two rotations about the x and y axes, respectively. The seal ring response is also in five degrees of freedom. The interface is represented by cross coupled stiffness and damping coefficients that are obtained from other codes. The effects of Coulomb friction of the secondary seals on seal ring response are included. Figure 2 shows an inverted configuration with the initial radial pressure on the piston ring on its ID. This inside configuration results in less pressure loading on the ring because the ID area is less than the OD area. The reduced loading also reduces the secondary seal ring friction that may retard tracking. In addition to piston ring secondary seals, an O-ring secondary can also be applied.

Figure 3 shows a floating ring seal that can also be analyzed by the code. This configuration permits two degrees of freedom for both the shaft and ring, and is intended to determine seal ring response to an orbiting shaft. The secondary seal occurs between the ring and the wall and x-y Coulomb friction at that location is accounted for.

The method of computation is a forward integration in time that provides absolute motions in all degrees of freedom. The reason that this approach was chosen was because of complications caused by Coulomb friction. At every time step, friction has to be evaluated to determine if motions continue or are halted.

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* For the reader's convenience, figures are presented at the end of each section.
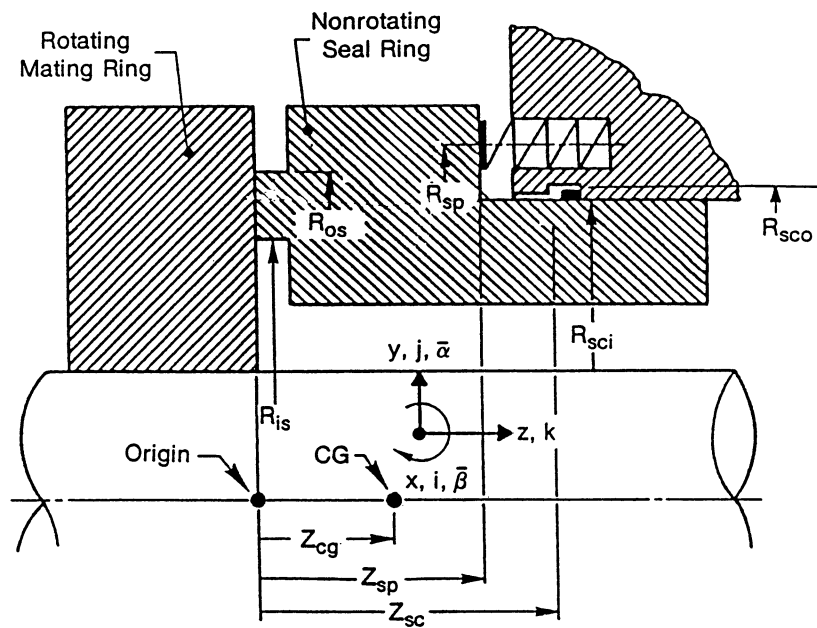
Figure 1. Fluid Film Face Seal Parameters
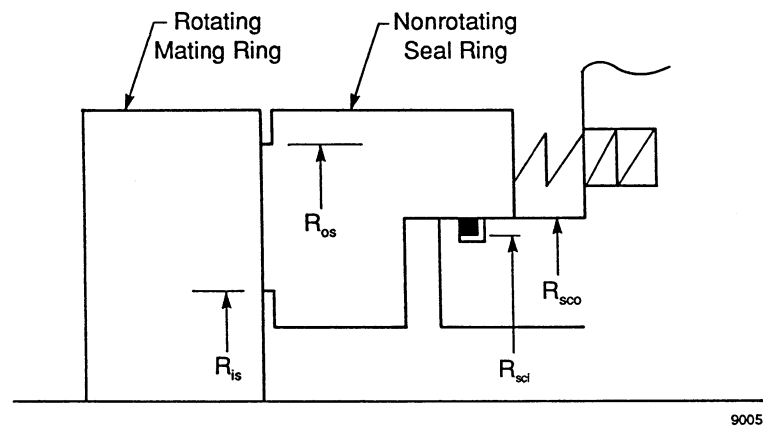
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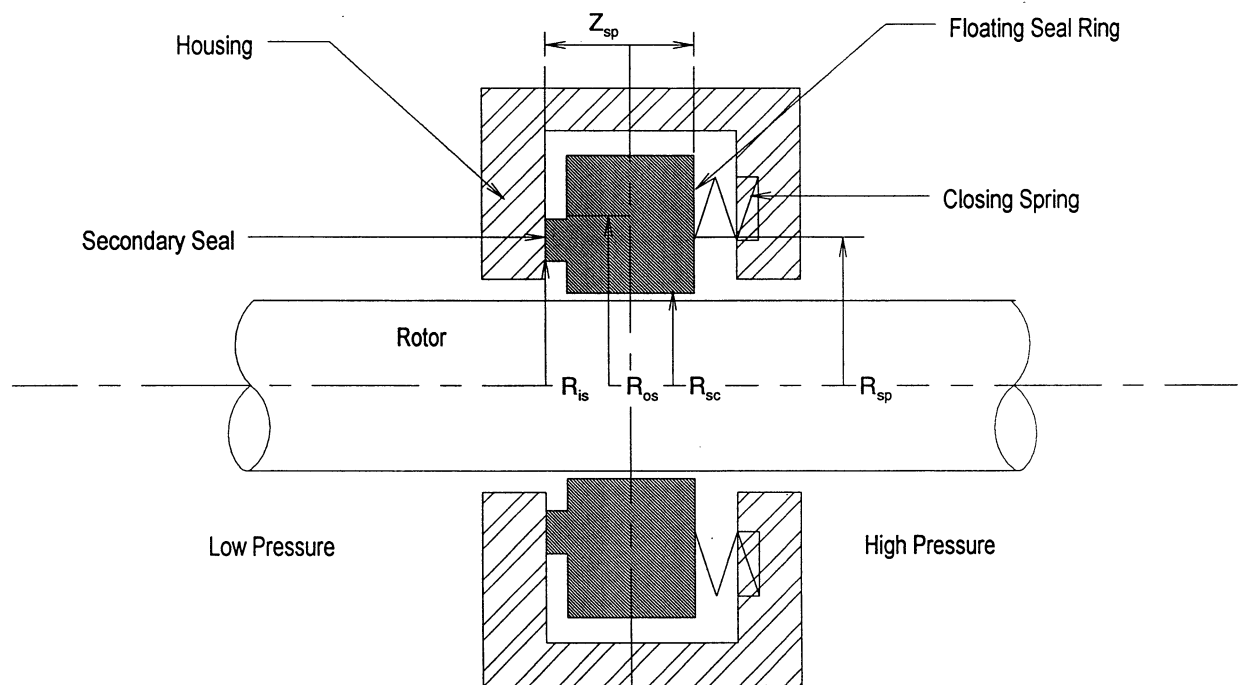
Figure 3. Floating Ring Seal

2.0 THEORY

The code determines the response of the seal ring in five degrees of freedom to shaft vibrations in as many as five degrees of freedom. These degrees of freedom are:

1. x_s = seal ring displacement in x direction.
2. y_s = seal ring displacement in y direction.
3. z_s = seal ring displacement in z direction.
4. β_s = seal ring rotation about x-x axis.
5. α_s = seal ring rotation about y-y axis.

Note that throughout this manual, seal motions are subscripted with an s and shaft motions are nonsubscripted. Unit vectors are $\hat{i}$, $\hat{j}$, and $\hat{k}$ in the x, y, and z directions, respectively. Coulomb friction is accounted for in both the secondary seal and the interface.

2.1 Equations of Motion

Considering small motions, the following equations apply:

$$\sum \vec{F}_x = m\ddot{x}_s \tag{2.1}$$

$$\sum \vec{F}_y = m\ddot{y}_s \tag{2.2}$$

$$\sum \vec{F}_z = m\ddot{z}_s \tag{2.3}$$

$$\sum \vec{M}_x = I_t \ddot{\beta}_s \tag{2.4}$$

$$\sum \vec{M}_y = I_t \ddot{\alpha}_s \tag{2.5}$$

where m = mass of seal ring and I_t = transverse moment of inertia of seal ring.

2.2 Development of Newmarks' Method

The solution to the equations of motion are obtained by the use of Newmarks' method or the average acceleration method [1]*. The velocity $\dot{U}_{i+1}$ at a time station, i+1 is approximated as

$$\dot{U}_{i+1} = \dot{U}_i + \left(\frac{\ddot{U}_i + \ddot{U}_{i+1}}{2} \right) \Delta t_i \tag{2.6}$$

Similarly,

$$U_{i+1} = U_i + \left(\frac{\dot{U}_i + \dot{U}_{i+1}}{2} \right) \Delta t \tag{2.7}$$

---

* Numbers in brackets indicate references that can be found in Section 7.0.

If the value of $\dot{U}_{i+1}$ from Equation (2.7) is substituted into Equation (2.6), the following equation results:

$$U_{i+1} = U_i + \dot{U}_i \Delta t + \left(\frac{\ddot{U}_i + \ddot{U}_{i+1}}{4} \right) \Delta t^2 \tag{2.8}$$

but

$$\ddot{U}_{i+1} = M^{-1} \left\{ F_{i+1} - KU_{i+1} - D\dot{U}_{i+1} \right\} \tag{2.9}$$

where M = mass matrix; F = unbalanced force vector; K = stiffness matrix; and D = damping matrix.

Substituting Equation (2.9) into (2.8) produces:

$$U_{i+1} \left(\frac{4}{\Delta t^2} + KM^{-1} \right) = \frac{4}{\Delta t^2} U_i + \frac{4}{\Delta t} \dot{U}_i + \ddot{U}_i + M^{-1}F_{i+1} - DM^{-1}\dot{U}_{i+1} \tag{2.10}$$

Now from Equation (2.7),

$$\dot{U}_{i+1} = \frac{2U_{i+1}}{\Delta t} - \frac{2U_i}{\Delta t} - \dot{U}_i \tag{2.11}$$

Substituting Equation (2.11) into (2.10) and multiplying by M produces:

$$\left(\frac{4M}{\Delta t^2} + K + \frac{2D}{\Delta t} \right) U_{i+1} = F_{i+1} + \left(\frac{4M}{\Delta t^2} + \frac{2D}{\Delta t} \right) U_i + \left(\frac{4M}{\Delta t} + D \right) \dot{U}_i + M\ddot{U}_i \tag{2.12}$$

Thus, an expression has been derived that relates the displacement at the new time step to displacements, velocities, and accelerations at the prior time step.

Once U_{i+1} is obtained, $\dot{U}_{i+1}$ and $\ddot{U}_{i+1}$ are obtained from Equations (2.7) and (2.6), respectively.

$$\dot{U}_{i+1} = \frac{2}{\Delta t} \left[U_{i+1} - U_i \right] - \dot{U}_i \tag{2.13}$$

From Equation (2.6),

$$\ddot{U}_{i+1} = \frac{2}{\Delta t} \left[\dot{U}_{i+1} - \dot{U}_i \right] - \ddot{U}_i \tag{2.14}$$

Substituting Equation (2.13) into (2.14) gives:

$$\ddot{U}_{i+1} = \frac{4}{\Delta t^2}\left(U_{i+1} - U_i\right) - \frac{4}{\Delta t}\dot{U}_i - \ddot{U}_i \qquad (2.15)$$

Thus, displacements, velocities, and accelerations are determined from the results of previous time steps. Initially, these quantities equal zero. Computations are conducted in subroutine NEWMARK.

2.3 Solution Process

Figure 4 is a flow diagram of the program logic. The program computes the mass and inertia properties of the seal ring and the location of the center of gravity. After computing all constants and matrix elements that are independent of time, the program enters the time step loop. Shaft motions are incremented first. Using updated shaft motions, the secondary seal friction is determined. This includes friction magnitudes and direction in the x_s, y_s, z_s, β_s, and α_s directions as well as the friction components that go into the stiffness and damping matrices and force vector.

The force vector, F, is next updated because, as indicated in using Newmarks method, the most recent force vector, F_{i+1}, is required. Then, Newmarks method is applied and the new seal displacements, velocities, and accelerations are determined. Subsequent to the calculations, adjustments are made to these variables because of friction resistance. The following paragraphs describe the development of the theory for the individual steps in the solution process, as outlined in Figure 4.

2.4 Initialization

The initialization routine, INIT, initializes displacements, velocities, and acceleration prior to entering the time step loop. Initial displacements correspond to the shaft displacements at the first time step, so that the seal ring and shaft are in correspondence. Initial values of velocities and acceleration are nulled.

2.5 Mass Matrix

The code develops the mass and inertia properties from a series of connected ring elements. Up to 20 elements can be inputted with individual OD, ID, length, and density. From this input, the code determines the location of the center of gravity (CG), the mass, and the polar and transverse moments of inertia of the seal ring. The mass matrix and CG location are computed in the subroutine, STMASS. Computed values are included in program output.

2.6 Computation of Constants

The subroutine, CONST, computes variables of interest to the seal designer and also constant variables utilized by the code.

The closing area is the unbalanced hydraulic closing area that varies for the type of seal being analyzed. For a piston ring seal (Figure 1), the closing area is:

$$A_{CL} = \pi\left(R_{os}^2 - R_{sci}^2\right) \tag{2.16}$$

If an inside ring is employed (see Figure 2), then

$$A_{CL} = \pi\left(R_{os}^2 - R_{sco}^2\right) \tag{2.17}$$

For an O-ring secondary seal, there is no distinction between the inside and outside radii and the closing area is given by:

$$A_{CL} = \pi\left(R_{os}^2 - R_{sc}^2\right) \tag{2.18}$$

The same expression applies for a ring seal except that R_{sc} is taken as the inside radius of the seal.

The interface area is the mating area and is given (for all seals) by:

$$A_{IF} = \pi\left(R_{os}^2 - R_{is}^2\right) \tag{2.19}$$

Another area of interest is the difference between the interface and closing areas. The absolute difference between the interface and closing areas is:

$$A_{CLL} = \left|A_{CL} - A_{IF}\right| \tag{2.20}$$

For a face seal, the hydraulic closing force is:

$$F_{HCL} = P_H A_{CL} + P_L A_{CLL} \tag{2.21}$$

where P_H = high pressure and P_L = low pressure.

For ring seals,

$$F_{HCL} = P_H A_{CL} - P_L A_{CLL} \tag{2.22}$$

The code computes the spring preload by summing the preload from the individual springs.

For a piston ring, there will be initial preloads from the installation spring stiffness and from pressure on the ring circumference and on the ring face. The secondary seal preload per unit length for a ring pressurized on its OD is:

$$P_{re\ell} = P_H \frac{R_o w}{R_i} + (P_{e\ell})_i \qquad (2.23)$$

where $P_{re\ell}$ = preload per unit of circumference; R_o = outside radius of the piston ring; R_i = inside radius of the piston ring; w = the width of the piston ring; and $(P_{re\ell})$ = installed preload per unit of circumference.

The total preload is:

$$P_r = 2\pi R_i P_{re\ell} \qquad (2.24)$$

For an inside ring, R_L and R_o are reversed in computing $P_{re\ell}$.

For an O-ring seal, the preload per unit of circumference is an input quantity and the preload is given by Equation (2.24).

The face seal axial forces are a function of preload and the coefficient of friction, such that

$$F_{fz} = P_r \times \nu \qquad (2.25)$$

where F_{fz} = secondary seal friction in the axial direction and ν = coefficient of friction.

The initial interface preload includes components from closing pressure and spring load and is equal to:

$$F_{IF} = F_{HCL} + F_{SP} \qquad (2.25)$$

where F_{IF} = initial interface load and F_{SP} = initial spring closing load.

Subroutine CONST also computes the initial axial position of the seal ring accounting for secondary seal ring friction. For face seals, the equilibrium fluid film interface force is an input quantity. The procedure is to balance the closing loads by the fluid film load using the axial stiffness of the fluid film to determine position iterations. Figure 5 shows the algorithms used.

For a ring seal, the fluid film stiffness is replaced by the structural stiffness of the seal ring. Often, a soft material such as carbon is used for the seal ring and its initial compression and face load are of interest. The ring seal stiffness is approximated by:

$$K_{zz} = A_{IF} E / L$$

where A_{IF} = interface area; E = elastic modulus of the seal ring; and L = seal ring length.

2.7 Stiffness and Damping Outside of the Time Step Loop

There are stiffness and damping quantities that are invariant and can be matrixed outside of the time step loop.

2.7.1 Fluid Film Stiffness and Damping

The fluid film interfaces are represented by cross coupled stiffness and damping coefficients that are obtained from other codes. For face seals, the fluid film has three degrees of freedom (z, β, α) and the stiffness and damping quantities occupy the lower right portion of the 5 × 5 stiffness and damping matrix. The ring seal fluid film has two degrees of freedom (x and y) and the stiffness and damping values occupy the upper left portion of the matrices. Tables 1 and 2 show the locations of the stiffness and damping quantities.

2.7.2 Spring Stiffnesses

The total spring force is (see Figure 6):

$$\overline{F}_{sp} = k_{sp} \sum_{i=1}^{Nsp} \delta_{sp}^i \tag{2.27}$$

where $\overline{F}_{sp}$ = total spring force; k_{sp} = spring stiffness; δ_{sp}^i = displacement of ith spring; and N_{sp} = number of springs. (Note: the spring preload does not enter into the equations of motion.) The displacement of the ith spring is:

$$\delta_{sp}^i = \left(\overline{\delta}_{cg} + \overline{\phi}_s \times \overline{r}_{sp}^i \right) \cdot \hat{k} \tag{2.28}$$

where

$$\overline{\delta}_{cg} = \text{displacement of cg} = \begin{Bmatrix} x_s \\ y_s \\ z_s \end{Bmatrix}$$

$$\overline{\phi}_s = \text{rotation of seal ring about axis through cg} = \begin{Bmatrix} \beta \\ \alpha \\ o \end{Bmatrix}$$

$$\overline{r}_{sp}^i = \text{vector from cg to ith spring} = \begin{Bmatrix} R_{sp} \cos \theta^i \\ R_{sp} \sin \theta^i \\ z_{sp} \end{Bmatrix}$$

Table 1. Stiffness Coefficients

F \ Δ	X	Y	Z	β	α
F_x	K_{xx}	K_{yy}			
F_y	K_{yx}	K_{yy}			
F_z			K_{zz}	$K_{z\beta}$	$K_{z\alpha}$
M_x			$K_{\beta z}$	$K_{\beta\beta}$	$K_{\beta\alpha}$
M_y			$K_{\alpha z}$	$K_{\alpha\beta}$	$K_{\alpha\alpha}$

Ring Seals (upper-left block), Face Seals (lower-right block)

95TM1

Table 2. Damping Coefficients

F \ Δ	X	Y	Z	β	α
F_x	D_{xx}	D_{yy}			
F_y	D_{yx}	D_{yy}			
F_z			D_{zz}	$D_{z\beta}$	$D_{z\alpha}$
M_x			$D_{\beta z}$	$D_{\beta\beta}$	$D_{\beta\alpha}$
M_y			$D_{\alpha z}$	$D_{\alpha\beta}$	$D_{\alpha\alpha}$

Ring Seals (upper-left block), Face Seals (lower-right block)

95TM1

The moments of the spring forces about the center of gravity are:

$$\overline{M}_{sp} = \sum_{i=1}^{N_{sp}} \overline{r}_{sp}^{i} \times \overline{F}_{sp}^{i} = \begin{Bmatrix} M_{xx} \\ M_{yy} \\ o \end{Bmatrix} \tag{2.29}$$

The axial stiffness of the spring is:

$$N_{sp} \cdot k_{sp} \tag{2.30}$$

Rotational stiffness can be obtained explicitly.

$$K_{sp}^{i,j} = \frac{M_{sp}^{i,j}(j+\delta_j) - M_{sp}^{i,j}(j)}{\Delta j} \tag{2.31}$$

For a single spring, the rotational spring constant is:

$$K_{spt} = \frac{k_{sp} R_{sp}^{2}}{2} \tag{2.32}$$

The program numerically computes the spring stiffnesses and then adds them to the stiffness matrix for Newmarks computations.

Stiffness and damping are also computed for the O-ring secondary seals, and is presented in Section 2.14 along with the discussion of O-ring friction, which is a parameter whose direction varies with time.

2.8 Shaft Increments

Shaft motions are incremented inside the time step loop according to the following equations:

$$x = x_o \cos \omega_x t \tag{2.33}$$
$$y = y_o \sin \omega_y t \tag{2.34}$$
$$z = z_o \sin \omega_z t \tag{2.35}$$
$$\beta = \beta_o \cos \omega_\beta t \tag{2.36}$$
$$\alpha = \alpha_o \sin \omega_\alpha t \tag{2.37}$$

where x = shaft displacement in x direction; y = shaft displacement in y direction; z = shaft displacement in z direction; β = shaft rotation about x axis; and α = shaft rotation about y axis.

To simulate circular orbits, x and y are 90° out of phase. The amplitudes x_o, y_o, etc., are input quantities and can be arbitrary to simulate elliptical shaft orbits. Also, the frequencies of vibration, ω_x, ω_y, etc., are input quantities and can be varied arbitrarily at the discretion of the

user. Velocities and accelerations are computed by taking derivatives in the usual manner. Shaft motions are computed in subroutine SHAFT.

2.9 Updating [K] and [D]

For a ring seal, the fluid film stiffness and damping are constant quantities but their components in x and y vary with the position of the shaft, and thus they must be updated inside of the time step loop. Basically, the input values of K_{xx}, K_{xy}, etc., are values that are parallel and normal to the eccentricity vector. Referring to Figure 7, the position of the eccentricity vector varies as the shaft orbits. As shown in Figure 7, the eccentricity is along the x′ axis. Then, for the primed axes,

$$F' = -K'\delta' - D'\dot{\delta}' \qquad (2.38)$$

where

$$F' = \begin{Bmatrix} F'_x \\ F'_y \end{Bmatrix}$$

and

$$K' = \begin{bmatrix} K'_{xx} & K'_{xy} \\ K'_{yx} & K'_{yy} \end{bmatrix}$$

which are input quantities

$$\delta' = \begin{Bmatrix} \delta'_x \\ \delta'_y \end{Bmatrix}$$

$$\dot{\delta}' = \begin{Bmatrix} \dot{\delta}'_x \\ \dot{\delta}'_y \end{Bmatrix}$$

$$D' = \begin{bmatrix} D'_{xx} & D'_{yx} \\ D'_{yx} & D'_{yy} \end{bmatrix}$$

The forces along x′, y′ must be transposed along x and y

$$F = AF' \qquad (2.39)$$

where

$$F = \left\{ \begin{array}{c} F_x \\ F_y \end{array} \right\}$$

$$A = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

Substituting Equation (2.38) into (2.39), we obtain

$$F = A\left[-k'\delta' - D'\dot{\delta}' \right] \tag{2.40}$$

but $\delta' = A^T\delta$ and $\dot{\delta} = A^T\dot{\delta}$. Therefore,

$$F = -AK'A^T\delta - AD'A^T\dot{\delta} \tag{2.41}$$

but, F also equals

$$F = -K\delta - D\dot{\delta} \tag{2.42}$$

where

$$K = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}$$

$$D = \begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix}$$

Therefore, comparing Equations (2.41) and (2.42)

$$K = AK'A^T \text{ and } D = AD'A^T \tag{2.43}$$

The code determines the position of the eccentricity vector by calculating the position of the minimum film thickness. The stiffness and damping transformations are accomplished in subroutine RSTD and appropriately added to the stiffness and damping matrices for NEWMARK computations.

2.10 Viscous Shear Forces and Moments

For face seals, viscous shear forces are produced at the interface. These forces are

$$F = \frac{-\mu A V}{h} \tag{2.44}$$

$$F = \left\{ \begin{matrix} F_x \\ F_y \end{matrix} \right\} \tag{2.45}$$

$$V = \left\{ \begin{matrix} V_x \\ V_y \end{matrix} \right\} \tag{2.46}$$

where

A = interface area
V = seal ring velocity in x-y plane
h = film thickness
μ = absolute viscosity

The coefficients $\mu A/h$ are included in the damping matrix.

2.11 Applied Forces

The computation of applied forces and moments are necessary for subsequent friction computations. The applied force vector includes all forces and moments excluding equilibrium and friction forces and moments.

For ring seals,

$$F_a = -K(\delta_s - \delta) - D(\dot{\delta}_s - \dot{\delta}) \tag{2.47}$$

where:

$$F_a = \text{applied force vector} = \left\{ \begin{matrix} F_{ax} \\ F_{ay} \end{matrix} \right\}$$

$$K = \text{film stiffness matrix} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}$$

$$D = \text{film damping matrix} = \begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix}$$

$$\delta_s = \text{seal ring displacement} = \begin{Bmatrix} \delta_{sx} \\ \delta_{sy} \end{Bmatrix}$$

$$\delta = \text{shaft displacement} = \begin{Bmatrix} \delta_x \\ \delta_y \end{Bmatrix}$$

Similarly, $\dot{\delta}_s$ and $\dot{\delta}$ are seal ring and shaft velocity vectors, respectively.

For face seals, the matrix formulation is:

$$F_a = -K\delta_r - D\dot{\delta}_r \qquad\qquad\qquad (2.48)$$

where:

$$F_a = \text{applied force vector} = \begin{Bmatrix} F_{ax} \\ F_{ay} \\ F_{az} \\ M_{ax} \\ M_{ay} \end{Bmatrix}$$

$$\delta_r = \text{relative displacement vector} = \begin{Bmatrix} x_s \\ y_s \\ z_s - z \\ \beta_s - \beta \\ \alpha_s - \alpha \end{Bmatrix}$$

$$\dot{\delta}_r = \text{relative velocity vector} = \begin{Bmatrix} \dot{x}_s \\ \dot{y}_s \\ \dot{z}_s - \dot{z} \\ \dot{\beta}_s - \dot{\beta} \\ \dot{\alpha}_s - \dot{\alpha} \end{Bmatrix}$$

The forces from x and y displacements occur between the secondary seal and housing and are not relative with respect to the shaft.

Subscript, s, refers to the seal ring. Displacements without subscripts refer to the shaft motions. The elements of the stiffness and damping matrices are:

$$K_{11} = -K_x^{sc} = \text{O-ring stiffness in x direction}$$

$$K_{22} = -K_y^{sc} = \text{O-ring stiffness in y direction}$$

$$K_{33} = -K_z^{sp} + K_{zz} = \text{spring stiffness + fluid film stiffness in z direction}$$

$$K_{34} = K_{z\beta} = \text{cross coupled film stiffness}$$

$$K_{35} = K_{z\alpha} = \text{cross coupled film stiffness}$$

$$K_{43} = K_{\beta z} = \text{cross coupled film stiffness}$$

$$K_{44} = -K_\beta^{sp} + K_{\beta\beta} = \text{spring rotational stiffness + film stiffness about x axis}$$

$$K_{45} = K_{\beta\alpha} = \text{cross coupled film stiffness}$$

$$K_{53} = K_{\alpha z} = \text{cross coupled film stiffness}$$

$$K_{54} = K_{\alpha\beta} = \text{cross coupled film stiffness}$$

$$K_{55} = -K_\alpha^{sp} + K_{\alpha\alpha} = \text{spring rotational stiffness about y axis + film rotational stiffness.}$$

The damping matrix includes the viscous shear damping:

$$D_{11} = D_{SH} - D_{xx}^{sc} = \text{shear damping coefficient + O-ring damping in x direction}$$

$$D_{15} = -D_{SH}z_{cg} = \text{shear damping coefficient} \times \text{axial distance to cg}$$

$$D_{22} = D_{SH} - D_{yy}^{sc} = \text{shear damping coefficient + O-ring damping in y direction}$$

$$D_{25} = D_{SH}z_{cg} = \text{shear damping coefficient} \times \text{axial distance to cg}$$

$$D_{33} = D_{zz} = \text{film damping coefficient}$$

$$D_{34} = D_{z\beta} = \text{cross coupled film damping coefficient}$$

$$D_{35} = D_{z\alpha} = \text{cross coupled film damping coefficient}$$

$$D_{z42} = D_{SH}z_{cg} = \text{shear damping coefficient} \times \text{axial distance to cg}$$

$$D_{43} = D_{\beta z} = \text{cross coupled film damping coefficient}$$

$$D_{44} = D_{\beta\beta} + D_{SH}z_{cg}^2 = \text{film damping coefficient + shear damping coefficient} \times$$
the square of the cg distance

$$D_{45} = D_{\beta\beta} + D_{SH}z_{cg}^2 = \text{film damping coefficient + shear damping coefficient} \times$$
the square of the cg distance

$$D_{51} = -D_{SH}z_{cg} = \text{shear damping coefficient} \times \text{the distance to the cg}$$

$$D_{53} = D_{\alpha z} = \text{cross coupled film damping coefficient}$$

$$D_{54} = D_{\alpha\beta} = \text{cross coupled film damping coefficient}$$

$$D_{55} = D_{\alpha\alpha} + D_{SH}z_{cg}^2 = \text{cross coupled film damping + shear damping coefficient} \times$$
the square of the cg distance.

The applied forces and moments are computed in subroutine APP.

2.12 Piston Ring Secondary Seal Friction Forces and Moments

2.12.1 Friction Forces and Moments from the Radial Surface of the Piston Ring

The piston ring moves with the shaft in x and y, and can also hold back the shaft from moving (see Figure 8). Surface 2 of the piston ring is the radial face, and Surface 1 is the interior cylindrical surface. The velocity of Surface 2 is:

$$\overline{V}_{sc2} = \dot{x}_s \hat{i} + \dot{y}_s \hat{j} + \overline{\omega}_s \times \overline{r}_2$$
$$\overline{\omega}_s = \dot{\beta}_s \hat{i} + \dot{\alpha}_s \hat{j}$$

(2.49)

$$\overline{r}_2 = z_1 \hat{k} + r_f \cos\theta \hat{i} + r_f \sin\theta \hat{j}$$

(2.50)

$$\overline{\omega}_s \times \overline{r}_2 = -\dot{\beta}_s z_1 \hat{j} + \dot{\beta}_s r_f \sin\theta \hat{k} + \dot{\alpha}_s z_1 \hat{i} - \dot{\alpha}_s r_f \cos\theta \hat{k}$$

(2.51)

It is assumed that there is zero k velocity of the piston ring. Therefore:

$$\overline{V}_{sc2} = (\dot{x}_s + \dot{\alpha}_s z_1)\hat{i} + (\dot{y}_s - \dot{\beta}_s z_1)\hat{j} = V\hat{i}_{sc2x} + V\hat{j}_{sc2y}$$

(2.52)

The direction of the friction force is opposite to that of the velocity

$$\overline{F}_{sc2} = \text{friction force} = -p_o A_p v \frac{\overline{V}_{sc2}}{|V_{sc2}|}$$

(2.53)

where:

p_o = applied pressure on piston ring
A_p = unbalanced contact area of piston ring
v = coefficient of friction

and

$$F_{sc2x} = -p_o A_p v \text{ (sign Vsczx)}$$

(2.54)

$$F_{sc2y} = -p_o A_p v \text{ (sign Vsczy)}$$

(2.55)

The moment about the CG from the face friction force is:

$$\overline{M}_2 = \overline{r}_2 \times \overline{F}_{sc2} = (z_1 \hat{k} + r_f \cos\theta \hat{i} + r_f \sin\theta \hat{j}) \times (F_{sc2x} \hat{i} + F_{sc2y} \hat{j})$$
$$= z_1 F_{sc2x} \hat{j} - z_1 F_{sc2y} \hat{i} + k \text{ components that are neglected.}$$

(2.56)

where F_{sc2x} and F_{sc2y} are defined above.

These friction forces and moments are computed in the subroutine FRICWALL. They are subsequently added to the force vector in the Newmark formulations.

2.13 Friction Forces From the ID of the Piston Ring

At the ID piston ring interface, there is only velocity in the z direction, which equals the relative velocity of the seal ring in the z direction. The major contribution to the normal force at the ID is the pressure that p_o applies to the OD. The following equation results for the load per unit length at the ID of the piston ring.

$$P_{e\ell} = \frac{p_o R_{sco} w}{R_{sci}} + P'_{e\ell} \tag{2.57}$$

where:

$P_{e\ell}$ = preload per unit length of ID of piston ring
p_o = pressure on OD of piston ring
R_{sco} = outside radius of piston ring
R_{sci} = inside radius of piston ring
w = width of contact surface at ID
$P'_{e\ell}$ = initial or installed preload per unit length

The direction of the friction force is opposite the direction of the axial velocity, $\overline{V}_z$. If $\overline{V}_z = 0$, the direction of the friction force is opposite the direction of the applied force in the z direction, $\overline{F}_{az}$. Therefore,

$$F_f = -2\pi v R_{sci} P_{e\ell} \left(\text{sign } \overline{V}_z \text{ or sign } \overline{F}_{az}\right) \tag{2.58}$$

Computations are made in the subroutine SFRIC.

2.14 O-Ring Secondary Seal Stiffness and Friction Forces and Moments

An O-ring secondary seal contributes stiffness and damping and friction forces and moments. Explicit analysis was conducted to determine these contributions. The O-ring is divided into 72 segments of 5 degrees each. The displacement of the ℓth segment is:

$$\overline{\delta}^\ell = \overline{u} + \overline{\phi} \times \overline{r}_{se}^\ell \tag{2.59}$$

where:

$$\overline{\delta}^\ell = \left\{ \begin{array}{c} \overline{\delta}_x^\ell \\ \delta_y^\ell \\ \delta_z^\ell \end{array} \right\}, \quad \overline{u} = \left\{ \begin{array}{c} u_1 \\ u_2 \\ 0 \end{array} \right\}, \quad \phi = \left\{ \begin{array}{c} \beta_s \\ \alpha_s \\ 0 \end{array} \right\}, \quad r_{sc}^\ell = \left\{ \begin{array}{c} R_{sc} \cos\theta^\ell \\ R_{sc} \sin\theta^\ell \\ z_{sc} - u(3) \end{array} \right\}$$

The normal vector at θ^ℓ is $\hat{n}^\ell$ (Figure 9), where

$$\hat{n}^\ell = \cos\theta^\ell \hat{i} + \sin\theta^\ell \hat{j} \qquad (2.60)$$

$$\overline{\delta}^\ell \cdot \hat{n}^\ell = \delta_n^\ell \qquad (2.61)$$

where δ_n^ℓ = normal displacement at θ^ℓ. Similarly, the velocity of the seal ring at the ℓth segment is:

$$\overline{\dot{\delta}}^\ell = \overline{\dot{u}} + \overline{\dot{\phi}} \times \overline{r}_{sc}^\ell$$

where (2.62)

$$\overline{u} = \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ 0 \end{Bmatrix}, \quad \overline{\phi} = \begin{Bmatrix} \dot{\beta}_s \\ \dot{\alpha}_s \\ 0 \end{Bmatrix}$$

and

$$\dot{\delta}_n^\ell = \dot{\delta}^\ell \cdot \hat{n}^\ell \qquad (2.63)$$

The normal force at the ℓth segment on the seal ring is:

$$F_n^\ell = -k_{e\ell}\delta_n^\ell R_{sc}d\theta^\ell - D_{e\ell}\dot{\delta}_n^\ell R_{sc}d\theta^\ell - Pr_{e\ell}\cdot R_{sc}d\theta^\ell \qquad (2.64)$$

where:

$k_{e\ell}$ = O-ring stiffness per unit length
$D_{e\ell}$ = O-ring damping per unit length
$Pr_{e\ell}$ = O-ring preload per unit length
F_n^ℓ = normal O-ring force at θ^ℓ

and

$$F_x^\ell = F_n^\ell \cos\theta^\ell \qquad (2.65)$$

$$F_y^\ell = F_n^\ell \sin\theta^\ell \qquad (2.66)$$

$$F_x = \sum_{\ell=1}^{72} F_x^\ell \qquad (2.67)$$

$$F_y = \sum_{\ell=1}^{72} F_y^\ell \qquad (2.68)$$

where:

F_x^ℓ = x force at θ^ℓ

F_y^ℓ = y force at θ^ℓ

F_x = total O-ring x force

F_y = total O-ring y force

The O-ring moment is:

$$\overline{M}^\ell = \overline{r}_{se}^\ell \times \overline{F}_n^\ell \qquad (2.69)$$

and

$$\overline{M}^\ell = \begin{Bmatrix} M_x^\ell \\ M_y^\ell \\ M_z^\ell \end{Bmatrix}$$

where:

$\overline{M}^\ell$ = moment due to the normal force at θ^ℓ

and

$$M_x = \sum_{\ell=1}^{72} M_x^\ell, \qquad M_y = \sum_{\ell=1}^{72} M_y^\ell \qquad (2.70)$$

The stiffness of the O-ring is:

$$K_{ij} = \frac{F_i(\delta_j)}{\delta_j} \qquad (2.71)$$

where:

K_{ij} = ith stiffness in the i direction due to a j displacement

δ_j = displacement in j direction.

These stiffnesses are determined from a zero displacement position and are constant values. They are added to the stiffness matrix that is used in the NEWMARKS routine. Similarly,

$$D_{ij} = \frac{F_i(\delta_j)}{\dot{\delta}_j} \qquad \cdot (2.72)$$

where:

$$D_{ij} = \text{damping in i direction due to a j velocity.}$$

The O-ring friction imposes additional forces and moments on the seal ring. The friction forces are always along the z axis and direction is always opposite the velocity vector. The relative velocity at sector ℓ is:

$$\overline{V}_z^\ell = \left(\overline{\dot{u}}^\ell + \overline{\dot{\phi}} \times \overline{r}_{se}^\ell \right) \cdot \hat{k} \tag{2.73}$$

Then the friction force at the ℓth segment is:

$$F_f^\ell = \nu F_n^\ell \left(-\text{sign} V_z^\ell \right) \tag{2.74}$$

where ν = the coefficient of friction. The total friction force is:

$$F_f = \sum_{\ell=1}^{72} F_f^\ell \tag{2.75}$$

The moment due to the friction force is:

$$\overline{M}_f = \sum_{\ell=1}^{72} \left(\overline{r}_{sc}^\ell \times \overline{F}_f^\ell \right) \tag{2.76}$$

$$\overline{F}_f = \begin{Bmatrix} 0 \\ 0 \\ F_f \end{Bmatrix}, \quad \overline{M}_f = \begin{Bmatrix} M_x \\ M_y \\ 0 \end{Bmatrix} \tag{2.77}$$

These forces and moments are added to the force vector used in the NEWMARK routine.

2.15 Computation of the Force Vector

The force vector contains all terms that are not directly multiplied by the seal ring displacements, velocities, or accelerations.

$$m\ddot{x}_s + kx_s + D\dot{x}_s = F \tag{2.78}$$

where:

m = mass matrix
k = stiffness matrix
D = damping matrix
F = force vector
x_s, $\dot{x}_s$, $\ddot{x}_s$ = seal ring displacement, velocity, and acceleration vectors

The terms of the force vector, F, contain stiffness and damping multiplied by shaft displacements and velocities plus friction restraint force:

$$F = kx + D\dot{x} + F_f$$

where

F_f = friction vector
K = fluid film stiffness matrix
D = fluid film damping matrix plus viscous shear damping terms
F_f = friction restraint forces in all degrees of freedom

2.16 Friction Restraint

After the displacements, velocities, and accelerations are updated, it is necessary to determine whether friction should have halted the motion. When determining friction restraint, it is important to realize that total forces and velocities are applied, and considering components alone can be misleading. For example, a body moving in a plane will not be restrained in a component direction as long as the total applied force exceeds the total friction force even though a component friction force can exceed a component applied force. For purposes of illustration, a piston ring secondary seal will be discussed. Referring back, Figure 8 showed the piston ring model.

Wall friction on the piston ring will restrain lateral (x and y) and angular (α and β) motions of the seal ring. The ID friction of the piston ring will restrain axial motions of the seal ring. Consider a velocity versus time plot, as shown on Figure 10.

There are three regions of accountability:

1. When accelerating, F_f and F_a are opposite $|F_f| < |F_a|$
   - F_f = friction force
   - F_a = applied force.

2. When decelerating, F_f and F_a are of the same sign; a finite velocity implies $|F_f| < |F_a|$.

3. If the velocity changes sign between successive time steps, then somewhere between motion has stopped and cannot restart until $|F_a| > |F_f|$. Thus, there is a discontinuity in the velocity curve. If we followed the normal procedure without taking into account the finite stopping time, the velocity would be repositioned to point B in Figure 10 instead of point A.

At the piston ring wall, the velocities of the ring in the x and y directions are:

$$V_x = \dot{x} + \dot{\alpha} z_1 \tag{2.79}$$

$$V_y = \dot{y} - \dot{\beta} z_1 \tag{2.80}$$

and the total velocity is:

$$V_T = \sqrt{V_x^2 + V_y^2} \tag{2.81}$$

where:

V_x = x component of velocity of piston ring
V_y = y component of velocity of piston ring
$\dot{x}$ = x component of velocity of seal ring at CG
$\dot{y}$ = y component of velocity of seal ring at CG
α = rotational velocity about y axis
β = rotational velocity about x axis
z_1 = axial distance from CG to piston ring wall

The forces that would move the piston ring along the wall (x-y plane) come from both the lateral applied forces at the CG and the total applied moments about the CG.

$$F_{axt} = F_{ax} + M_{yy} / z_1 \tag{2.82}$$

$$F_{ayt} = F_{ay} - M_{xx} / z_1 \tag{2.83}$$

where:

F_{ax} = x component of applied force at CG
F_{ay} = y component of applied force at CG
M_{yy} = applied moment about y axis
M_{xx} = applied moment about x axis
F_{axt} = total x component of applied force at ring wall
F_{ayt} = total y component of applied force at ring wall

The total applied force at the ring wall is F_a, defined as:

$$F_a = \sqrt{F_{axt}^2 + F_{ayt}^2} \tag{2.84}$$

Other parameters include:

$$V_{xy} = \sqrt{\dot{x}^2 + \dot{y}^2} \tag{2.85}$$

where V_{xy} = total translatory velocity at CG.

$$F_{axy} = \sqrt{F_{ax}^2 + F_{ay}^2} \qquad\qquad (2.86)$$

where F_{axy} = total translatory applied force at CG. The friction force at the wall is defined as:

$$F_f = \sqrt{F_{fx}^2 + F_{fy}^2} \qquad\qquad (2.87)$$

where:

F_f = total friction force
F_{fx} = friction force in x direction
F_{xy} = friction force in y direction.

With these terms and definitions, a flow chart of the friction wall restraining algorithm is indicated on Figure 11. Note that even though friction may not restrain piston ring motion, a check has to be made on x and y motions at the CG. This is because the piston ring can move due to angular rotations about the CG without x, y translations of the CG.

A similar routine has been established for restraint in the z direction. Since this is a single-degree-of-freedom motion, it is a much simpler algorithm than for the coupled x, y and angular modes.

2.17 Minimum Film Thickness

At each time step, the minimum film thickness is computed to determine if a negative film occurs. If so, the computations are halted and the seal is considered failed.

Face Seal. Because of angular rotations, the minimum film thickness is computed at the outside radius of the fluid-film interface. The film thickness varies around the circumference of the seal and is thus a function of theta. In computing the film thickness, the circumference is subdivided into 72 increments, and the film thickness determined at each incremental intersection.

$$H_p = H_o + \Delta Z + \overline{\phi} \times \overline{r}_p \cdot \hat{k} \qquad\qquad (2.88)$$

where:

H_o = equilibrium film thickness
ΔZ = difference between seal ring and shaft displacement
$\overline{\phi}$ = rotation vector
$\overline{r}_p$ = position vector from center of gravity to point p

For a face seal with a stationary (nonrotating) seal ring,

$$H = H_o + (Z_s - Z) + \left[\left((\beta_s - \beta)\hat{i} + (\alpha_s - \alpha)\hat{j}\right) \times \left(-z_{cg}\hat{k} + R_o \cos\theta_p\hat{i} + R_o \sin\theta_p\hat{j}\right)\right] \cdot \hat{k}$$

$$H = H_o + (Z_s - Z) + \left[(\beta_s - \beta)R_o \sin\theta_p - (\alpha_s - \alpha)R_o \cos\theta_p\right] \qquad (2.89)$$

Ring Seal Clearance. Ring seal parameters are shown on Figure 12. Ring seals are limited to two degrees of freedom, x and y. Since both the shaft and ring can move, the film thickness is a function of relative displacements between them. The equations are as follows:

$$\overline{\xi}_r = \overline{\xi}_s - \overline{\xi}$$
$$\overline{\phi}_r = \overline{\phi}_s - \phi$$
$$H = C + \overline{\xi}_r \cdot \hat{n} \tag{2.90}$$

where:

$\overline{\xi}_s$ = displacement vector of seal ring

$\overline{\xi}$ = displacement vector of shaft

$\overline{\xi}_r$ = relative displacement

and

$$\overline{\xi}_s = x_s \hat{i} + y_s \hat{j}; \quad \xi = x\hat{i} + y\hat{j}$$

$$\overline{\xi}_r = (x_s - x)\hat{i} + (y_s - y)\hat{j} \tag{2.91}$$

$$\hat{n} = \cos\theta \hat{i} + \sin\theta \hat{j} \tag{2.92}$$

$$\overline{\xi}_r \cdot \hat{n} = (x_s - x)\cos\theta + (y_s - y)\sin\theta \tag{2.93}$$

$$H = C + (x_s - x)\cos\theta + (y_s - y)\sin\theta = C + (x_s - x)\cos\theta + (y_s - y)\sin\theta \tag{2.94}$$

where:

z = longest distance from CG to end of seal.
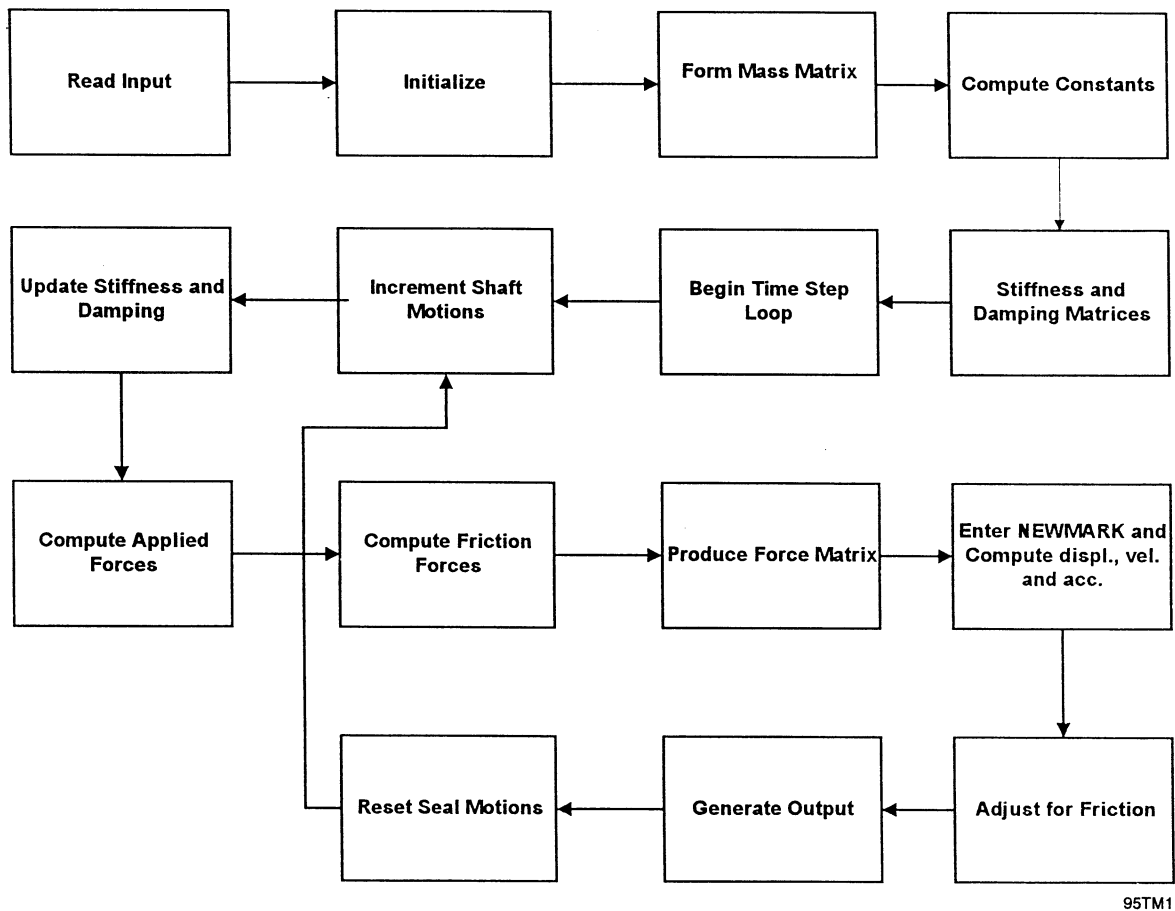
Figure 4. Program Flow Chart

$$F_a = F_{f\ell} - F_{if}$$

$$IF \left| F_a \right| .LT. \left| F_{fz} \right|$$

| Y | N |

$$\delta_z = 0$$

$$\delta_z = F_a / k_{zz}$$

$$\delta_z .GT. 0$$

| Y | N |

$$\delta_z = \delta_z - F_{fz} / k_{zz}$$

$$\delta_z = \delta_z + F_{fz} / k_{zz}$$

$$H_o = H_o + \delta_z$$
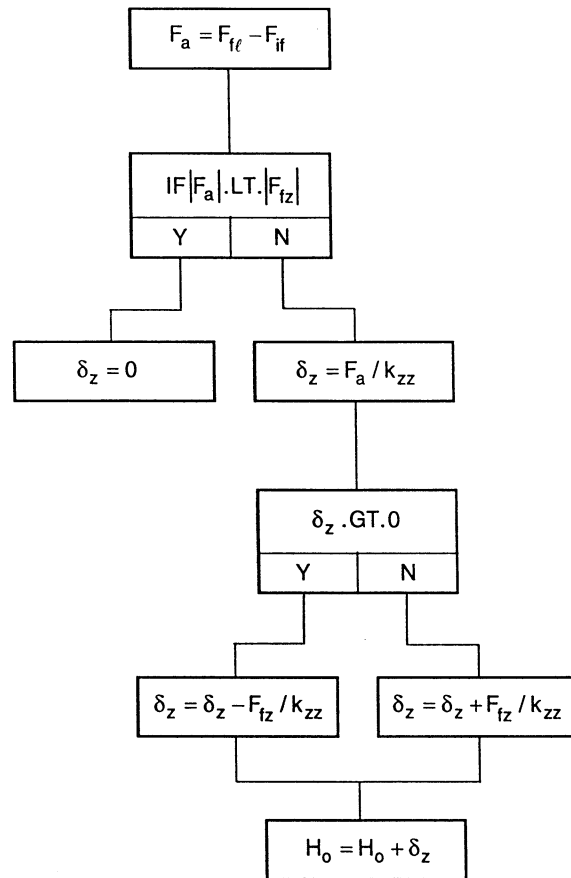
95TM1

F_a = Axial force

$F_{f\ell}$ = Fluid film force

F_{fz} = Axial friction force

δ_z = Axial seal ring displacement

k_{zz} = Fluid film axial stiffness coefficient

Figure 5. Initial Equilibrium Algorithm
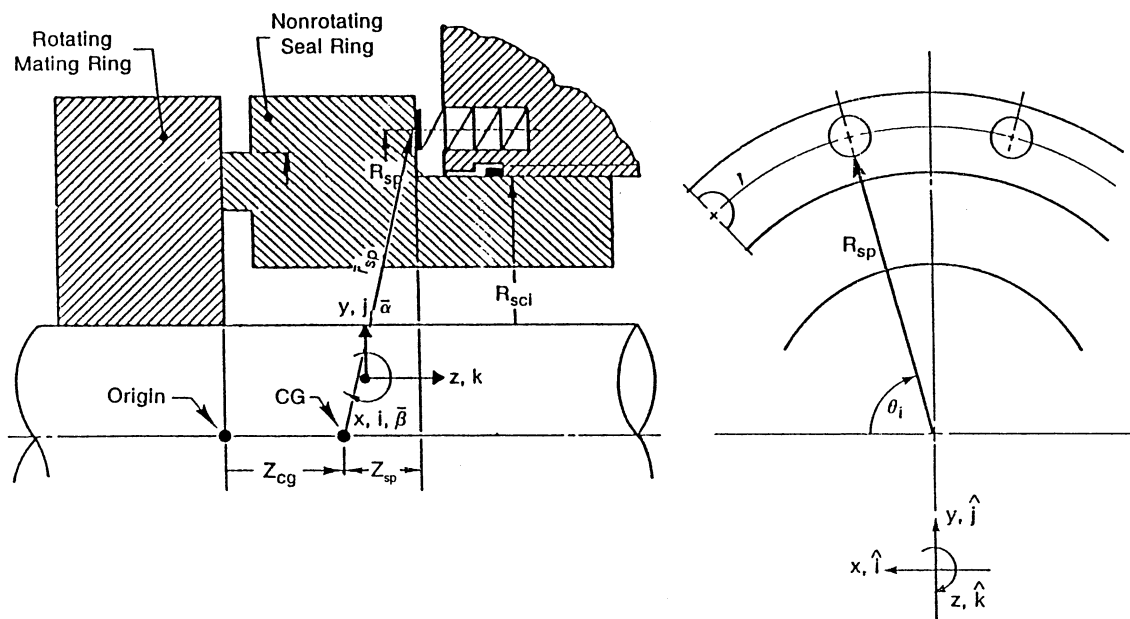
Figure 6. Spring Forces and Moments
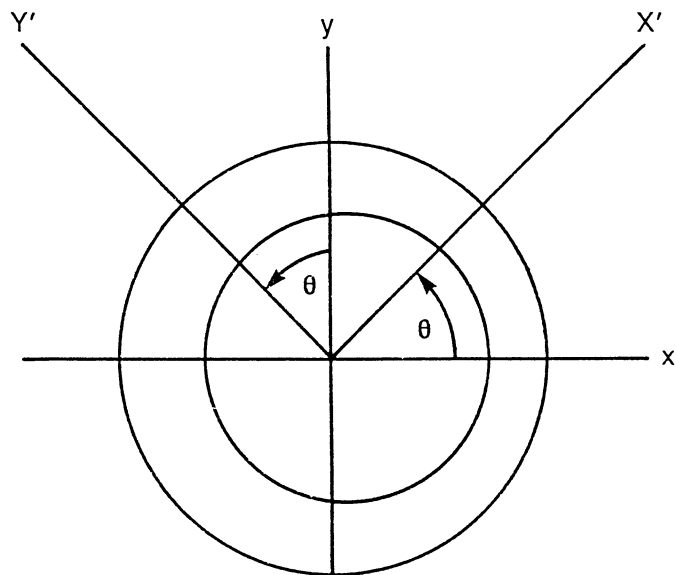
Figure 7. Ring Seal Transformations
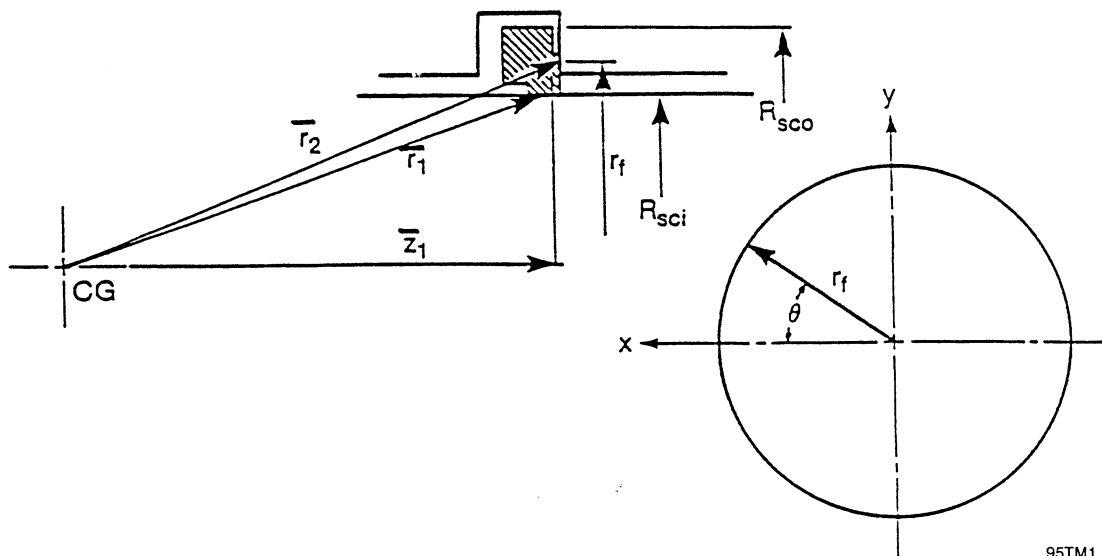
Figure 8. Piston Ring Forces and Moments
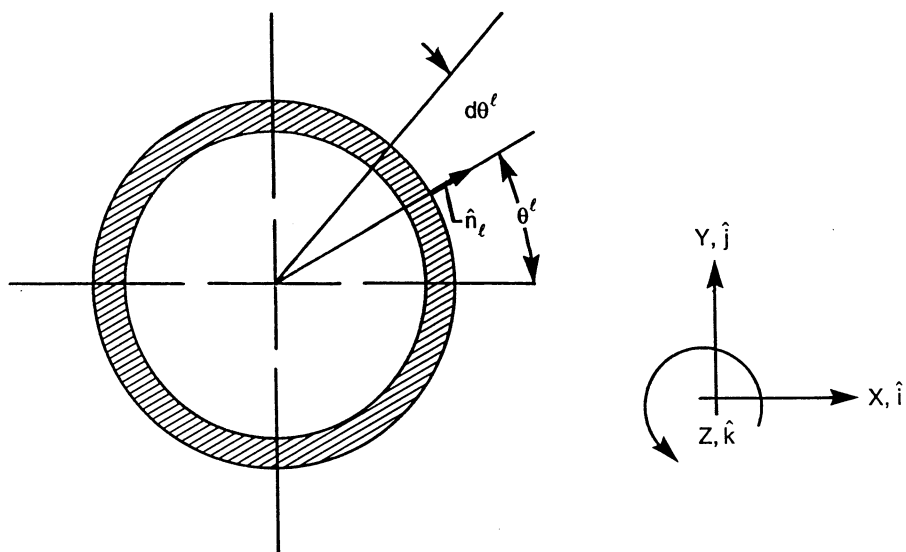
Figure 9. O-Ring Parameters
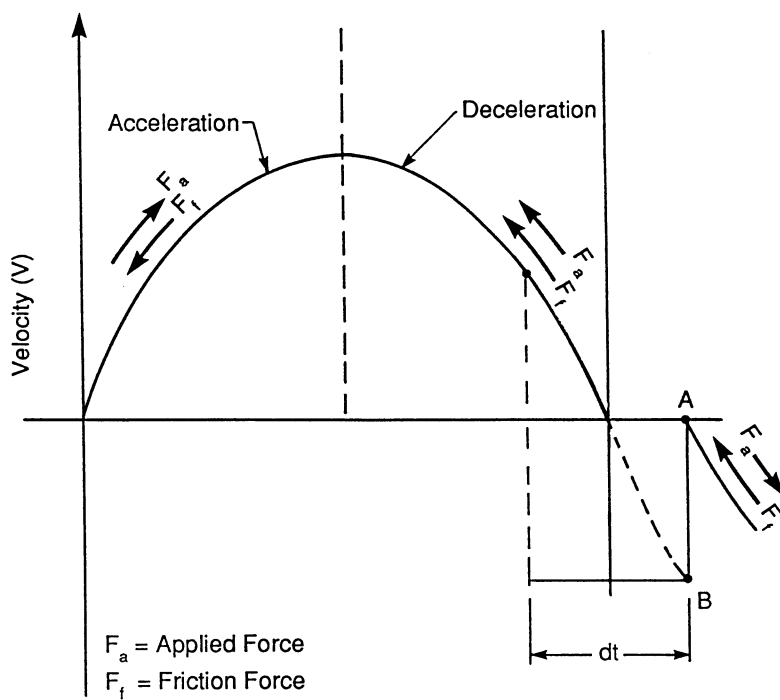
Figure 10. Velocity versus Time Including Friction Restraint
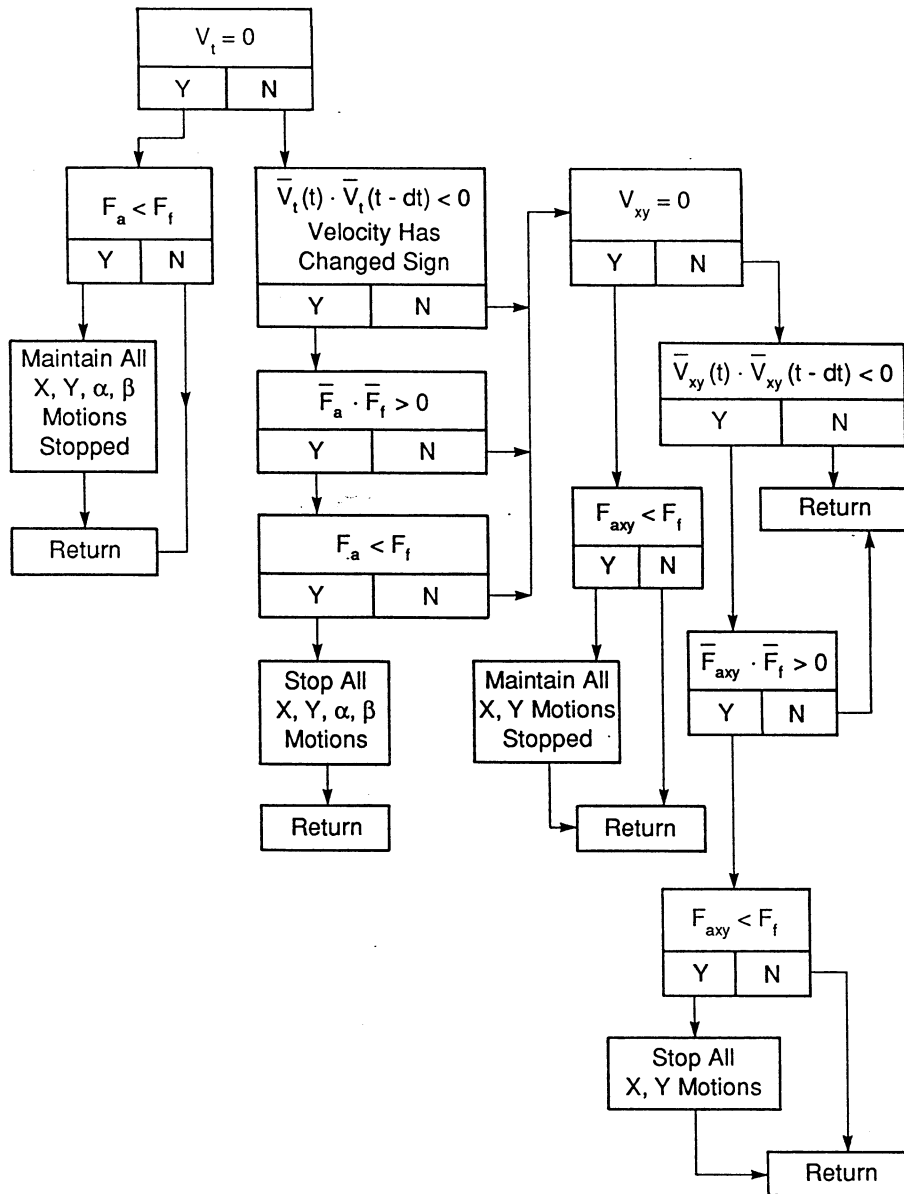
Figure 11. Flow Chart of Piston Ring Wall Friction Restraining Algorithm
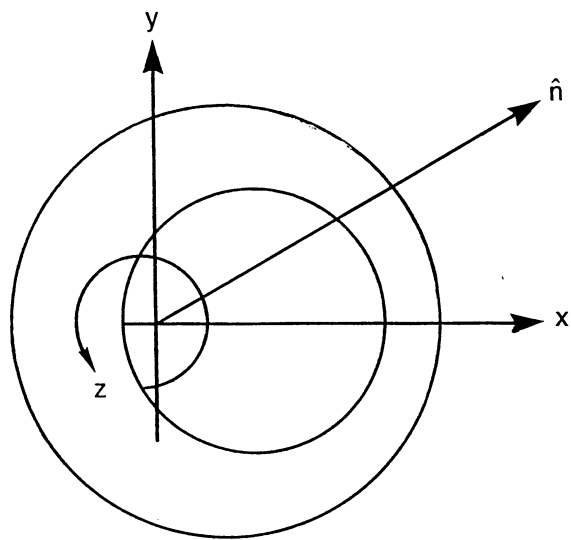
95071

Figure 12. Ring Seal Clearance

3.0 DESCRIPTION OF INPUT/OUTPUT

3.1 Input Variables

The input variables are described in Figure 13. There is one additional variable missing from the figure; it is the variable HELP. If HELP is identified in the input file list, then a figure similar to Figure 13 will be produced in the output. The input is divided into several groups. The separation of parameters are indicated by data set identifiers that categorize input quantities. The categories are as follows:

- Geometry
- Spring and damping coefficients
- Operating conditions
- Initial conditions
- Program continuation.

Referring to Figure 13 and Figure 1, the first series of input quantities concern the geometry of the seal ring. Most of the variables are self-explanatory. The variable NELM identifies the number of geometrical elements the seal ring is partitioned into to describe its geometry. Generally, a new element is introduced when there is a sharp variation in the inside or outside radius or where there is a material change. The program permits partitioning the seal ring into as many as 20 elements. The variables RIEL and ROEL are the inside and outside radii of the element, respectively, and the variable ELEML is the axial length of the element. The density of each element is described by the variable DENS. The variable ZL is the axial distance from the interface to the beginning of the element. If the seal ring and piston ring configurations are as were shown in Figure 2, then the variable INSIDE = 1.0 is inputted. If not, a default value of zero is used. The face area of the piston ring secondary seal that is in contact with the housing is the variable APR. The width of the ID of the piston ring in contact with the seal ring is WPR.

The next series of variables describes the spring and damping characteristics of various elements in the seal system. The closing springs provide a closing preload and an axial stiffness to the system. The variables SKXX through SKAA are associated with the fluid film on the face of the seal or the interior of the ring seal. SKZZ is the fluid film stiffness in the axial or z direction. SKZA is the cross coupled stiffness in the z direction due to a rotational displacement α about the y axis. The variable A refers to α (a rotation about the y axis), and B to β (a rotation about x axis). The cross coupled stiffness and damping matrices that represent the characteristics of the fluid film are each 3×3 matrices for face seals and 2×2 matrices for ring seals (see Section 2.7.1). These values are obtained from other sources. A positive stiffness provides a restoring force to a displacement. The variables DZZ, DZA, etc., are damping characteristics of the fluid film.

The third set of variables include FFL and HO, which are the equilibrium fluid film force and the value of the film thickness at the midpoint of the seal face. The variable CO is the radial clearance of the ring seal. Again, these values are obtained externally. Although for face seals FFL and HO must correlate, they do not have to be the precise equilibrium values with the closing forces, as the program will move the seal ring into the initial equilibrium and print out the results in the output.

The fourth and fifth sets of variables are concerned with the environmental operating conditions to which the seal is exposed and the initial conditions that start the process. The variable DT is related to the number of time steps per revolution as follows:

- $DT = 2\pi/(\omega\, N_s)$
- ω = rotational speed, rad/sec
- N_s = number of time steps per revolution.

If the value of DT is not chosen correctly, numerical instabilities will result that will be reflected in output exceeding formats or giving obviously incorrect numbers. In many instances, a value of $N_s = 100$ time steps/revolution works well. The time increment DT is a function of the distance traveled per time step. Large amplitude high-frequency motion requires small time increments, while small amplitude low-frequency motion allows for larger values of DT. It is generally worthwhile to experiment with the value of the time increment DT to ensure a proper value. At times, it is necessary to run cases with 300 to 500 time steps per revolution.

The next set of variables applies to a continuation of a case that has been previously run. Information to fill in this list of variables will have been provided by the output of the run to be continued. The subscripted variable U(5) refers to the five displacements: x, y, z, β, and α, respectively. The subscript 1 is x; 2 is y; 3 is z; 4 is β; and 5 is α.

3.2 Input Format

The first line of the input identifies the name of the output and plotting files without extension. Generally, this name is the same as the name of the input file (see Figure 16, Section 4.0). To run a case, the input file must be copied to DYSEAL.INP and the instruction DYSEAL executed. The output files and plotting files will be produced with the name provided as the first line of the input file. The second line of the input file can be a short description of the problem or title in Columns 1 through 80.

All input parameters start with the variable name.
- Columns 1 to 10, A10: variable name
- Columns 11 to 80, free format: variable quantity
- . . . . 80 columns total

The first 10 columns of each identifier are reserved for the key words that specify the input parameters (e.g., ZSCO in Figure 13). These key words must be entered starting at Column 1 of each line. Only the first six letters of each key word will be recognized by the program. These letters must be entered exactly as specified in the input instruction. The lines can be entered in any order except for the first title line. The user does not have to input a line that has a default value. If an asterisk is placed in Column 1, the input quantity will be ignored and the default value will be maintained.

Units. The units for the English and metric systems are as follows:

English
- Length: in.
- Density: $lb/in.^3$
- E: $lb/in.^2$
- Stiffness: lb/in., lb/rad, in.-lb/rad
- Damping: lb-sec/in., lb-sec/rad, in.-lb-sec/rad
- Rotational speed and frequency: rad/sec
- Viscosity: $lb-sec/in.^2$ (reyns)
- Pressure: $lb/in.^2$
- Force: lb
- Film thickness: in.

Metric
- Length: meters
- Density: kg/m^3
- E: N/m^2
- Stiffness: N/m, N/rad, N-m/rad
- Damping: N-s/m, N-s/rad, m-N-s/rad
- Rotational speed and frequency: rad/s
- Viscosity: $Pa-s = N-s/m^2$
- Pressure: $Pa = N/m^2$
- Force: N
- Film thickness: microns

3.3 Description of Output

There are two forms of output: computer printout and computer plots.

3.3.1 Computer Printout

The printout consists of a description of the input parameters, as shown on Figure 14, if the variable HELPS is included in the input file. This is followed by a printout of the input values, as shown on Figure 14. The computer code calculates some specific significant parameters, such as mass, CG distance, and the polar and transverse moments of inertia about the CG. Following are computations of the hydraulic closing area (ACL) and the hydraulic closing force (FHCL), which is the high pressure multiplied by the closing area. The interface area (AIF) is the contact face area of the seal. The balance ratio of the seal is ACL/AIF. If the ratio is ≤1, then the seal is balanced; if the ratio is ≥1, the seal is unbalanced. For any given fluid film geometry, the higher the unbalance, the greater will be the tendency of the seal to close.

The variable, FIFPRE, is the interface preload that includes all closing forces on the seal, (hydraulic plus spring load). SCFRIC is the restraining friction on the seal ring from the secondary seal, and HO is the initial equilibrium film thickness. The value of HO may be different from that originally inputted to place the seal ring in equilibrium with the closing forces. However, if the axial friction force SCFRIC is sufficient to prevent initial movement, the initial value of the film thickness will remain as specified. The final set of values produced as printed output are the variables required for continuation of the case, as shown on Figure 14.

3.3.2 Plotted Output

To facilitate interpreting dynamic results, plotted output is essential. The program has been organized to write output out on File 4, which is reread by a plotting routine, XYPLOT. The plotting routine is called by the command XYPLOT, which will display three menus. From the File Menu, select Open File and a list of file names in the directory will appear. The plotting files have the extension FIL. Opening an FIL file will initiate the plots for that file. The abscissa and ordinate are selected from Plot Options. Manual selection of scales, grids, and rectangular or square appearance are obtained from the Axes heading in the Plot Menu. The plot line attributes and symbols come from the Lines selection in the Plot Menu. Data Labels and Fonts are also available from the Plot Menu. Printing is provided through the File Menu.

A panel will appear on the screen along with menus. Under the File Menu, open the current directory containing the output files. Then, double-click the .FIL extension of the file to be plotted. Under the Plot Menu, select Plot Options for plotting parameters selected by the user. Scales, grid, and plot shape (square or rectangular) can be altered under the Axes selection in the Plot Menu. To print a plot, select the Print option under the File Menu. Program output is discussed in Section 4.0.

```
C *** INPUT DESCRIPTION GEOMETRY ***
      DATA NAM1/
     +'ZSCO      =AXIAL DISTANCE TO SECONDARY SEAL
     +'ROS       =OUTSIDE RADIUS OF SEAL INTERFACE
     +'RIS       =INSIDE RADIUS OF SEAL INTERFACE
     +'RSCI      =PISTON RING INSIDE RADIUS
     +'RSCO      =PISTON RING OUTSIDE RADIUS
     +'RSC       =O-RING SECONDARY SEAL RADIUS
     +'RSP       =MEAN SPRING RADIUS
     +'ZSPO      =AXIAL DISTANCE TO CLOSING SPRINGS
     +'THETO     =ANGLE TO FIRST CLOSING SPRING
     +'DTHET     =ANGLE BETWEEN SPRINGS,
     +'NELM      =NUMBER OF GEOMETRICAL ELEMENTS
     +'RIEL(20)  =INSIDE RADIUS OF ELEMENT
     +'ROEL(20)  =OUTSIDE RADIUS OF ELEMENT
     +'ELEML(20) =ELEMENT LENGTH
     +'DENS(20)  =ELEMENT DENSITY
     +'EMOD      =ELASTIC MODULUS OF RING SEAL
     +'APR       =UNBALANCED PISTON RING FACE AREA
     +'WPR       =CIRCUMFERENTIAL PISTON RING WIDTH
     +'ZL(20)    =AXIAL DIST. FROM INTERFACE TO ELEM.
     +'INSIDE    =1, ID PISTON RING
     +'PISTON    = TRUE IF SECONDARY PISTON RING
     +'ORING     = TRUE IF SECONDARY O-RING
     +'RING      = TRUE FOR A RING SEAL
     +'TOTAL     = TRUE FOR FORMATTED PRINTOUT
     +'NUNIT     = 1 FOR ENG.(DEFAULT), 2 FOR METRIC

C * ALSO INSIDE RADIUS OF RING SEAL
C
C *** INPUT DESCRIPTION SPRING AND DAMPING ***
      DATA NAM2A/
     +'SPPRE     =SINGLE SPRING PRELOAD
     +'NOSP      =NUMBER OF SPRINGS
     +'SKXX      =FLUID-FILM STIFFNESS, KXX
     +'SKXY      =FLUID-FILM STIFFNESS, KXY
     +'SKYX      =FLUID-FILM STIFFNESS, KYX
     +'SKYY      =FLUID-FILM STIFFNESS, KYY
     +'SKZZ      =FLUID-FILM STIFFNESS, KZZ
     +'SKZB      =FLUID-FILM STIFFNESS, KZB
     +'SKZA      =FLUID-FILM STIFFNESS, KZA
     +'SKBZ      =FLUID-FILM STIFFNESS, KBZ
     +'SKBB      =FLUID-FILM STIFFNESS, KBB
     +'SKBA      =FLUID-FILM STIFFNESS, KBA
     +'SKAZ      =FLUID-FILM STIFFNESS, KAZ
     +'SKAB      =FLUID-FILM STIFFNESS, KAB
     +'SKAA      =FLUID-FILM STIFFNESS, KAA

      DATA NAM2B/
     +'DYY       =FLUID-FILM DAMPING
     +'DYX       =FLUID-FILM DAMPING
     +'DXY       =FLUID-FILM DAMPING
     +'DXX       =FLUID-FILM DAMPING
     +'DZZ       =FLUID-FILM DAMPING
     +'DZB       =FLUID-FILM DAMPING
     +'DZA       =FLUID-FILM DAMPING
     +'DBZ       =FLUID-FILM DAMPING
     +'DBB       =FLUID-FILM DAMPING
     +'DBA       =FLUID-FILM DAMPING
     +'DAZ       =FLUID-FILM DAMPING
     +'DAB       =FLUID-FILM DAMPING
     +'DAA       =FLUID-FILM DAMPING
     +'SPRST     =CLOSING SPRING STIFFNESS
     +'FFL       = EQUILIBRIUM FLUID-FILM FORCE
     +'HO        = EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
C
```

```
     +'CO        = RING SEAL CLEARANCE
     +'SKEL      = O-RING STIFFNESS PER UNIT LENGTH
     +'DEL       = O-RING DAMPING PER UNIT LENGTH
     +'SCPREL    = O-RING AND PISTON RING PRELOAD PER UNIT LENGTH
C
C *** INPUT DESCRIPTION OPERATION ***
C
      DATA NAM3/
     +'OMEGA     =SHAFT ROTATIONAL SPEED
     +'POD       =OD PRESSURE
     +'PID       =ID PRESSURE
     +'COFSC     =COEFFICIENT OF FRICTION,SECONDARY SEAL
     +'VISC      =FLUID FILM VISCOSITY
     +'DT        =VALUE OF TIME STEP INCREMENT
     +'NTS       =NUMBER OF TIME STEPS
     +'NT        =INITIAL TIME STEP NUMBER
C
C *** INPUT DESCRIPTION INITIAL CONDITIONS ***
C
      DATA NAM4/
     +'XO        = SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
     +'YO        = SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
     +'ZO        = SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
     +'BO        = SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
     +'AO        = SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
     +'OMEGAX    = SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
     +'OMEGAY    = SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
     +'OMEGAZ    = SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
     +'OMEGAB    = SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
     +'OMEGAA    = SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S
     +'TINIT     = INITIAL TIME, SEC
     +'CONT      = TRUE IF THE RUN IS A CONTINUATION
C
C *** INPUT DESCRIPTION FOR CONTINUATION
C   (FOR CONTINUING A CASE ONLY) ***
C
      DATA NAM5/
     +'U(5)      =SEAL DISPLACEMENTS
     +'UDOT(5)   =SEAL VELOCITIES
     +'UDOTT(5)  =SEAL ACCELERATIONS
     +'FRICX     =FRICTION FORCE IN X DIRECTION
     +'FRICY     =FRICTION FORCE IN Y DIRECTION
     +'FRICZ     =FRICTION FORCE IN Z DIRECTION
     +'FRICB     =FRICTION MOMENT ABOUT X-X AXIS
     +'FRICA     =FRICTION MOMENT ABOUT Y-Y AXIS
C
```

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Figure 13. Input Variables for DYSEAL

ECHO OF INPUT

DYSEAL SAMPLE INPUT

*

DYSEAL INPUT INSTRUCTIONS
ZSCO   =AXIAL DISTANCE TO SECONDARY SEAL
ROS   =OUTSIDE RADIUS OF SEAL INTERFACE
RIS   =INSIDE RADIUS OF SEAL INTERFACE
RSCI   =PISTON RING INSIDE RADIUS
RSCO   =PISTON RING OUTSIDE RADIUS
RSC   =O-RING SECONDARY SEAL RADIUS
RSP   =MEAN SPRING RADIUS
ZSPO   =AXIAL DISTANCE TO CLOSING SPRINGS
THETO   =ANGLE TO FIRST CLOSING SPRING
DTHET   =ANGLE BETWEEN SPRINGS,
NELM   =NUMBER OF GEOMETRICAL ELEMENTS
RIEL(20)   =INSIDE RADIUS OF ELEMENT
ROEL(20)   =OUTSIDE RADIUS OF ELEMENT
ELEML(20)   =ELEMENT LENGTH
DENS(20)   =ELEMENT DENSITY
EMOD   =ELASTIC MODULUS OF RING SEAL
APR   =UNBALANCED PISTON RING FACE AREA
VPR   =CIRCUMFERENTIAL PISTON RING WIDTH
ZL(20)   =AXIAL DIST. FROM INTERFACE TO ELEM.
INSIDE   =1, ID PISTON RING
PISTON   = TRUE IF SECONDARY PISTON RING
ORING   = TRUE IF SECONDARY O-RING
RING   = TRUE FOR A RING SEAL
TOTAL   = TRUE FOR FORMATTED PRINTOUT
NUNIT   = 1 FOR ENG.(DEFAULT), 2 FOR METRIC

SPPRE   =SINGLE SPRING PRELOAD
NOSP   =NUMBER OF SPRINGS
SKXX   =FLUID-FILM STIFFNESS, KXX
SKXY   =FLUID-FILM STIFFNESS, KXY
SKYX   =FLUID-FILM STIFFNESS, KYX
SKYY   =FLUID-FILM STIFFNESS, KYY
SKZZ   =FLUID-FILM STIFFNESS, KZZ
SKZB   =FLUID-FILM STIFFNESS, KZB
SKZA   =FLUID-FILM STIFFNESS, KZA
SKBZ   =FLUID-FILM STIFFNESS, KBZ
SKBB   =FLUID-FILM STIFFNESS, KBB
SKBA   =FLUID-FILM STIFFNESS, KBA
SKAZ   =FLUID-FILM STIFFNESS, KAZ
SKAB   =FLUID-FILM STIFFNESS, KAB
SKAA   =FLUID-FILM STIFFNESS, KAA

DYY   =FLUID-FILM DAMPING
DYX   =FLUID-FILM DAMPING
DXY   =FLUID-FILM DAMPING
DXX   =FLUID-FILM DAMPING
DZZ   =FLUID-FILM DAMPING
DZB   =FLUID-FILM DAMPING
DZA   =FLUID-FILM DAMPING
DBZ   =FLUID-FILM DAMPING
DBB   =FLUID-FILM DAMPING
DBA   =FLUID-FILM DAMPING

DAZ   =FLUID-FILM DAMPING
DAB   =FLUID-FILM DAMPING
DAA   =FLUID-FILM DAMPING
SPRST   =CLOSING SPRING STIFFNESS
FFL   = EQUILIBRIUM FLUID-FILM FORCE
HO   = EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
CO   = RING SEAL CLEARANCE
SKEL   = O-RING STIFFNESS PER UNIT LENGTH
DEL   = O-RING DAMPING PER UNIT LENGTH
SCPREL   = O-RING AND PISTON RING PRELOAD PER UNIT LENGTH

OMEGA   =SHAFT ROTATIONAL SPEED
POD   =OD PRESSURE
PID   =ID PRESSURE
COFSC   =COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC   =FLUID FILM VISCOSITY
DT   =VALUE OF TIME STEP INCREMENT
NTS   =NUMBER OF TIME STEPS
NT   =INITIAL TIME STEP NUMBER

XO   = SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO   = SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO   = SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
BO   = SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
AO   = SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
OMEGAX   = SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
OMEGAY   = SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
OMEGAZ   = SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
OMEGAB   = SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
OMEGAA   = SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S
TINIT   = INITIAL TIME, SEC
CONT   = TRUE IF THE RUN IS A CONTINUATION
SPPRE   =SINGLE SPRING PRELOAD

U(5)   =SEAL DISPLACEMENTS
UDOT(5)   =SEAL VELOCITIES
UDOTT(5)   =SEAL ACCELERATIONS
FRICX   =FRICTION FORCE IN X DIRECTION
FRICY   =FRICTION FORCE IN Y DIRECTION
FRICZ   =FRICTION FORCE IN Z DIRECTION
FRICB   =FRICTION MOMENT ABOUT X-X AXIS
FRICA   =FRICTION MOMENT ABOUT Y-Y AXIS

*GEOMETRY
PISTON   T   = TRUE IF SECONDARY PISTON RING
ZSCO   0.7120   =AXIAL DISTANCE TO SECONDARY SEAL
ROS   1.580   =OUTSIDE RADIUS OF SEAL INTERFACE
RIS   1.240   =INSIDE RADIUS OF SEAL INTERFACE
RSCI   1.220   =PISTON RING INSIDE RADIUS
RSCO   1.400   =PISTON RING OUTSIDE RADIUS
RSP   1.563   =MEAN SPRING RADIUS
NELM   3.000   =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO   0.2525   =AXIAL DISTANCE TO CLOSING SPRINGS
THETO   0.0000E+00   =ANGLE TO FIRST CLOSING SPRING
DTHET   0.5236   =ANGLE BETWEEN SPRINGS,
RIEL(20)   =INSIDE RADIUS OF ELEMENT
            1.025   1.025   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
            0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
            0.0000E+00 0.0000E+00 0.0000E+00

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Figure 14. Program Output

```
03/29/1995  23:40       Filename: SAMPLE1.OUT                                    Page 3

ROEL(20) =OUTSIDE RADIUS OF ELEMENT
   1.580        1.780        1.220        0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00
ELEML(20) =ELEMENT LENGTH
   0.9250E-01   0.1600       0.6125       0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00
DENS(20) =ELEMENT DENSITY
   0.2500       0.2500       0.2500       0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00
ZL(20)  =AXIAL DIST. FROM INTERFACE TO ELEM.
   0.2500E-01   0.9250E-01   0.2525       0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00
   0.0000E+00   0.0000E+00
APR    =  0.5360        =UNBALANCED PISTON RING FACE AREA
WPR    =  0.2500E-01    =CIRCUMFERENTIAL PISTON RING WIDTH
*SPRING AND DAMPING
SPPRE  =  0.1500          SINGLE SPRING PRELOAD
NOSP   =  12.00           NUMBER OF SPRINGS
SKZZ   =  0.4210E+06      FLUID-FILM STIFFNESS, KZZ
SKZA   =  0.0000E+00      FLUID-FILM STIFFNESS, KZA
SKZB   =  0.0000E+00      FLUID-FILM STIFFNESS, KZB
SKBZ   =  0.0000E+00      FLUID-FILM STIFFNESS, KBZ
SKBB   =  0.3612E+06      FLUID-FILM STIFFNESS, KBB
*SKBA  =  0.0
*SKAZ  =  0.0
*SKAB  =  0.0
SKAA   =  0.3612E+06      FLUID-FILM STIFFNESS, KAA
DZZ    =  0.0000E+00      FLUID-FILM DAMPING
DZB    =  0.0000E+00      FLUID-FILM DAMPING
DZA    =  0.0000E+00      FLUID-FILM DAMPING
DBZ    =  0.0000E+00      FLUID-FILM DAMPING
DBB    =  0.0000E+00      FLUID-FILM DAMPING
DBA    =  0.0000E+00      FLUID-FILM DAMPING
DAZ    =  0.0000E+00      FLUID-FILM DAMPING
DAB    =  0.0000E+00      FLUID-FILM DAMPING
DAA    =  0.0000E+00      FLUID-FILM DAMPING
SPRST  =  5.050           CLOSING SPRING STIFFNESS
HO     =  0.1170E-02      EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL    =  2375.           EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA  =  7330.           SHAFT ROTATIONAL SPEED
POD    =  750.0           OD PRESSURE
PID    =  0.0000E+00      ID PRESSURE
COFSC  =  0.2000          COEFFICIENT OF FRICTION, SECONDARY SEAL
VISC   =  0.1700E-07      FLUID FILM VISCOSITY
DT     =  0.8572E-05      VALUE OF TIME STEP INCREMENT
NTS    =  1000.           NUMBER OF TIME STEPS
NT     =  1.000           INITIAL TIME STEP NUMBER
*INITIAL CONDITIONS
XO     =  0.5000E-03      SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
```

```
03/29/1995  23:40       Filename: SAMPLE1.OUT                                    Page 4

YO      =  0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO      =  0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
AO      =  0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,R
AD.
BO      =  0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,R
AD.
OMEGAX  =  7330.         SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS,
RAD/S
OMEGAY  =  7330.         SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS,
RAD/S
OMEGAZ  =  7330.         SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS,
RAD/S
TINIT   =  0.0000E+00    INITIAL TIME, SEC
OMEGAB  =  7330.         SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS,
RAD/S
OMEGAA  =  7330.         SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS,
RAD/S
1

                 TOTAL MASS, LB.-SEC**2/IN =  0.1505581E-02
                 CG DISTANCE, IN. =   0.2895275
                 POLAR MOMENT OF INERTIA, LB-SEC**2-IN =   0.2626893E-02
                 TRANSVERSE MOMENT OF INERTIA, LB.-SEC**2-IN =   0.1397172E-02

                 ACL=CLOSING AREA, IN**2=   3.166725
                 FHCL=HYDRAULIC CLOSING FORCE, LBS.=   2375.044
                 AIF=INTERFACE AREA, IN**2,=   3.012159
                 FIFPRE=INTERFACE PRELOAD, LBS=   2376.844
                 SCFRIC=SECONDARY SEAL PRELOAD FRICTION, LBS=   32.98672
                 HO=INITIAL FILM THICKNESS OR INTERFERENCE, IN.=   0.1170000E-02

                 TO CONTINUE THIS CASE READ THE FOLLOWING         VARIABLES IN NAME
```

Figure 14. Continued

LIST CONTIN

```
NT=     1001
U(1)=   0.5029428E-03    U(2)= -0.2942818E-05    U(3)= -0.2870002E-03
U(4)=   0.6351748E-03    U(5)= -0.1935520E-03
UDOT(1)=   0.0000000E+00    UDOT(2)=  0.0000000E+00
UDOT(3)=   3.434496        UDOT(4)= -0.2241758
UDOT(5)=   4.711916
UDOTT(1)=  0.0000000E+00    UDOTT(2)=  0.0000000E+00
UDOTT(3)=  58354.43        UDOTT(4)= -59312.23
UDOTT(5)=  25723.67
FRICX= -80.40000    FRICY=  80.40000
FRICZ= -32.98672    FRICA= -33.99206
FRICB= -33.99206
```

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Figure 14. Continued

4.0 SAMPLE PROBLEMS

The sample problems included in this section are intended to demonstrate program usage and do not necessarily represent seal designs. Face seal samples are included in this section. Ring seal sample problems are demonstrated in the verification section where output was compared against published data.

4.1 Sample Problem 1: Piston Ring Face Seal Input

The sample problem analyzes the 50-mm spiral-groove seal described in Reference 2. Key geometrical parameters are shown in Figure 15. The seal ring was partitioned into three elements. The first element was the seal ring face. The inside radius of the seal ring face was taken as the same as that of the other two elements, since the actual length of the inside radius of the face is very thin (~0.20 in.). Input is shown in Figure 16. Spring and damping coefficients were taken from the work reported upon in Reference 2. The shaft displacements were 0.0005 in. and rotations were 0.0005 radians, respectively. The input format shown in Figure 16 follows the procedures identified in Section 3.0.

4.2 Sample Problem 1: Printed Output

The printed output for Sample Problem 1 has previously been described in Section 3.0 and is repeated in Figure 17. Since the variable HELP was included in the input file, input definitions are printed as part of the printed output.

4.3 Sample Problem 1: Plotted Output

Plotted output is shown in Figures 18 through 29. In some cases, multiple plots were employed, such as in Figure 18, which shows the x displacement of the seal ring, XS, and the x displacement of the shaft, X. The shaft displacements are sinusoidal patterns, while the seal ring displacements are the generally lower amplitude and more irregular response, due to secondary seal friction.

4.4 Sample Problem 2: Continuation

Sample Problem 2 is a continuation of Sample Problem 1, for another 5 revolutions or 500 time steps. The input to Sample Problem No. 1 is modified as indicated in Figure 30. The variables modified are: NTS (number of time steps) = 1500 and NT (initial time step) = 1001. Also, all the variables in input set CONTIN must be included. These are obtained from the printed output of Sample Problem No. 1, Figure 19. Printed output is shown in Figure 31. One plot of minimum film thickness was made and is shown in Figure 32.

4.5 Sample Problem 3

Sample Problem 3 is identical to Sample Problem 1, except the logical variable TOTAL is applied. Use of this variable allows formatted output to be printed. The formatted output is produced in three groupings. The first group presents seal motions and clearance; the second group shows shaft motions and minimum film thickness; and the final group shows friction forces and moments. Figures 33 and 34 show problem input and output, respectively.

4.6 Sample Problem 4: Metric Units

This problem is identical to Sample Problem 3, except metric units have been applied. The variable NUNIT is included in the input and given a value of 2. This problem also includes the variable TOTAL for formatted output. Input and output are shown in Figures 35 and 36, respectively.

4.7 Sample Problem 5: O-Ring Secondary Seal

The O-ring secondary seal introduces several new variables to the input process. The variables include:

- **SKEL (Secondary Seal Stiffness Per Unit Length).** SKEL is available from O-ring catalogs. Figure 37 shows percent compression versus load per lineal inch of seal for various O-ring cross sections and durometer. This figure was extracted from a Parker O-ring catalog. Percent compression is obtained by calculating the squeeze of the ring divided by the cross sectional width of the ring. This information is also obtainable from the catalog. The load per lineal inch divided by the squeeze gives the stiffness per unit length.

- **DEL (Secondary Seal Damping Per Unit Length).** Information is not available from O-ring catalogs. Elastomers are light damping devices, and a reasonable number for DEL = 1/(RSC π).

- **SCPREL (Secondary Seal Preload Per Unit Length).** Generally equal to SKEL, spring stiffness per unit length.

- **RSC (Radius to Secondary Seal)**

The input/output for this case is shown in Figures 38 and 39, respectively.

Figure 40 shows the x displacement of the seal ring versus shaft revolutions. The displacement is very small - on the order of 20×10^{-6} milli-radians. Similar results apply to the y motions shown on Figure 41. The only exciting forces in these modes is viscous shear between the mating ring and seal ring, which is a small value. Figure 42 shows the axial displacement of both

the runner and seal ring. The seal ring response is in phase and slightly magnified above the excitation. Rotations about the x-x and y-y axes are shown in Figures 43 and 44, respectively. The minimum film thickness as a function of shaft revolutions is indicated in Figure 45. Axial and rotational friction are shown in Figures 46 through 48.

4.8 Ring Seal Sample Problems and Verification

Ring seals are activated by the logical variable RING in the input file. The variable EMOD (elastic modulus) must be inputted or else a divide overflow will result. EMOD is used to determine the initial axial interference of the secondary seal with the wall.

For purposes of sample problems and verification, the ring seals described by Kirk in Reference 3 were analyzed. Kirk used a time transient scheme that varied the fluid film forces at each time step using short bearing theory. That differs from the approximate analysis used in DYSEAL in which the fluid film is represented by constant but rotating cross coupled stiffness and damping coefficients. Kirk also assumed a rotor modal mass supported on springs and dashpots and determined the response of the modal mass. In DYSEAL, rotor motions are prescribed.

The first case, as represented by Figure 49 (Kirk, Figure 7), included the following parameters:

- Speed = 1780 rpm
- Axial interface force = 20.9 lb
- Ring mass = 2.13 lb
- Clearance = 0.003 in.
- Length = 0.904 in.
- Viscosity = 0.8125×10^{-7} lb-sec/in.^{2}
- Friction coefficient = 0.150
- P_{high} = 72 psig
- P_{low} = 60 psig
- Shaft radius = 2.090 in.
- Rotor excursion = 0.0024 in.

The film stiffness and damping coefficients were obtained from external codes at an eccentricity ratio of 0.5. The eccentricity was chosen on the basis of load capacity to overcome the friction forces of the secondary seal. The cross coupled coefficients are indicated on the input file, Figure 50. A model was configured that simulated the mass of the ring and provided identical wall interface and friction forces. The given rotor orbit was circular at an eccentricity ratio of 0.8, or a finite value of 0.0024 in. This corresponds to the shaft eccentricity prescribed by Kirk. The problem output is shown in Figure 51. The given rotor circular orbit is indicated in Figure 52. Orbital response of the seal ring is shown in Figure 53. There is a significant amount of looping that occurs and the orbit is confined to the 0.0024-in. stimulus from the shaft. As shown at the bottom of Kirk's Figure 7, the orbit does loop.

overlapping of the looped orbit. Figure 54 shows the seal ring displacement as a function of shaft revolutions. Note that there is a strong half frequency component because of the strong cross coupling influence of the stiffness coefficients. The subsynchronous component further explains the orbital loops. Figure 55 shows the y displacement as a function of shaft revolutions. The minimum film thickness is indicated in Figure 56. From Kirk's Figure 7, the seal is tracking the rotor at approximately 0.5 eccentricity or with a minimum film of 1.5 mil. From Figure 56, the median of the film variation is approximately 1.5 mil. Figures 57 and 58 show the friction forces in the x and y direction, respectively. The comparative results are excellent, especially considering the differences in problem formulation.

A similar analysis was conducted for Kirk's Figure 8 problem (see Figure 59). This seal was identical to Kirk's Figure 7 problem except that the length of the seal was reduced from 0.904 to 0.600 in. This required the development of a new set of stiffness and damping coefficients. The input and output for this case are shown in Figures 60 and 61, respectively. The seal ring orbital response is shown in Figure 62. It is a complex pattern of interior looping. The minimum film thickness predicted by DYSEAL is shown in Figure 63. Kirk indicates the seal ring tracks at an eccentricity of 0.75 or at a minimum film thickness of 0.75 mils, which is verified on Figure 63. The minimum film thickness on Figure 63, however, is diminishing with revolutions and may eventually fail. Examination of Kirk's orbital plots reveal that the orbit is continuing to expand after the three revolutions that Kirk examined, and the orbit is not confined. If Kirk increased the number of revolutions, he may have come to the same conclusion as DYSEAL - that this ring may eventually fail by contact.

ELEML(1)
0.0925

ELEML(2)
0.160

ELEML(3)
0.6125

Rotating
Mating Ring

Nonrotating
Seal Ring

R_{oei}
(2)

R_{sp}

R_{os}

R_{oei}
(3)

R_{sco}

R_{iei}
(1,2,3)

R_{sci}

$y, j, \bar{\alpha}$

R_{is}

z, k

Origin

CG

$x, i, \bar{\beta}$

Z_{cg}

Z_{sp}

Z_{sc}
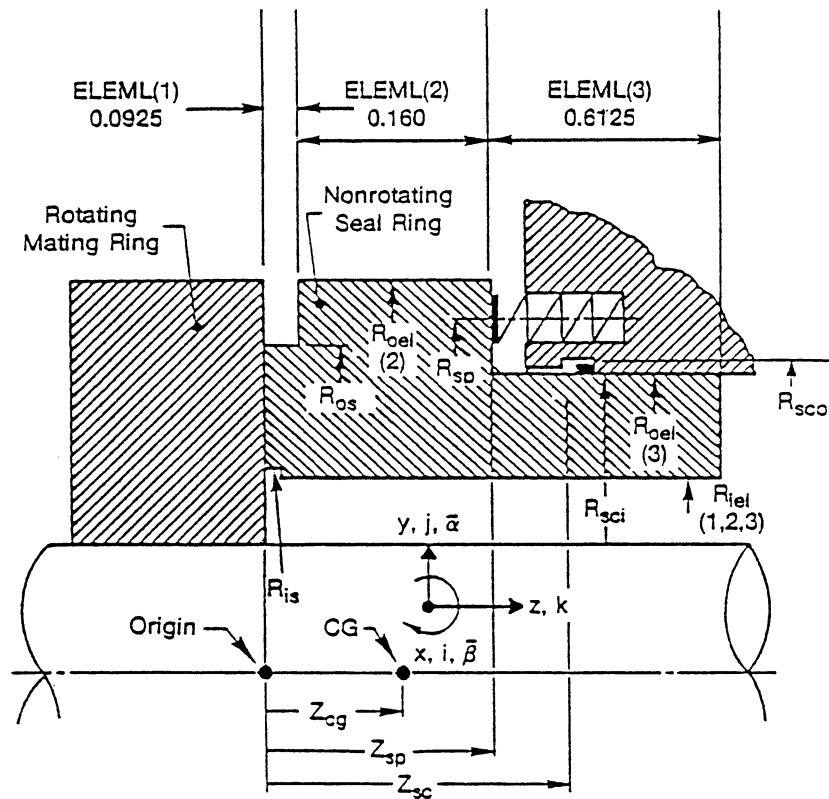
R_{os} = 1.58 in. R_{oei} (1) = R_{os} = 1.58 in. Z_{sp} = 0.2525 in.
R_{is} = 1.24 in. R_{oei} (2) = 1.78 in. Z_{sc} = 0.7120 in.
R_{sp} = 1.563 in. R_{oei} (3) = 1.22 in.
R_{sci} = 1.22 in. R_{iei} (1, 2, 3) = 1.025 in.
R_{sco} = 1.40 in.

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Figure 15. Geometry for Sample Problem 1

```
SAMPLE1
DYSEAL SAMPLE INPUT
*
HELP
*GEOMETRY
PISTON
ZSCO        0.712
ROS         1.58
RIS         1.24
RSCI        1.22
RSCO        1.40
RSP         1.5625
NELM        3
ZSPO        0.2525
THETO       0.0
DTHET       .5236
RIEL(20)    1.025   1.025   1.025
ROEL(20)    1.580   1.780   1.220
ELEML(20)   .0925   .1600   .6125
DENS(20)    .250    .250    .250
ZL(20)      0.0    .0925   .2525
APR         .536
WPR         .025
*SPRING AND DAMPING
SPPRE       .150
NOSP        12
SKZZ        421000.
SKZA        0.0
SKZB        0.0
SKBZ        0.0
SKBB        361239.
*SKBA       0.0
*SKAZ       0.0
*SKAB       361239.
SKAA        361239.
DZZ         0.0
DZB         0.0
DZA         0.0
DBZ         0.0
DBB         0.0
DBA         0.0
DAZ         0.0
DAB         0.0
DAA         0.0
SPRST       5.050
HO          .00117
FFL         2375.0
*OPERATING CONDITIONS
OMEGA       7330.
POO         750.
PID         0.0
COFSC       .2
VISC        1.7E-08
DT          8.571876E-06
NTS         1000
NT          1
*INITIAL CONDITIONS
XO          .0005
YO          .0005
ZO          .0005
AO          .0005
BO          .0005
OMEGAX      7330.
OMEGAY      7330.
OMEGAZ      7330.
TINIT       0.0

OMEGAB      7330.
OMEGAA      7330.
END
```

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Figure 16. Sample Problem 1 Input

```
ECHO OF INPUT

DYSEAL SAMPLE INPUT

*

DYSEAL INPUT INSTRUCTIONS
ZSCO      =AXIAL DISTANCE TO SECONDARY SEAL
ROS       =OUTSIDE RADIUS OF SEAL INTERFACE
RIS       =INSIDE RADIUS OF SEAL INTERFACE
RSCI      =PISTON RING INSIDE RADIUS
RSCO      =PISTON RING OUTSIDE RADIUS
RSC       =O-RING SECONDARY SEAL RADIUS
RSP       =MEAN SPRING RADIUS
ZSPO      =AXIAL DISTANCE TO CLOSING SPRINGS
THETO     =ANGLE TO FIRST CLOSING SPRING
DTHET     =ANGLE BETWEEN SPRINGS,
NELM      =NUMBER OF GEOMETRICAL ELEMENTS
RIEL(20)  =INSIDE RADIUS OF ELEMENT
ROEL(20)  =OUTSIDE RADIUS OF ELEMENT
ELEML(20) =ELEMENT LENGTH
DENS(20)  =ELEMENT DENSITY
EMOD      =ELASTIC MODULUS OF RING SEAL
APR       =UNBALANCED PISTON RING FACE AREA
VPR       =CIRCUMFERENTIAL PISTON RING WIDTH
ZL(20)    =AXIAL DIST. FROM INTERFACE TO ELEM.
INSIDE    =1, ID PISTON RING
PISTON    = TRUE IF SECONDARY PISTON RING
ORING     = TRUE IF SECONDARY O-RING
RING      = TRUE FOR A RING SEAL
TOTAL     = TRUE FOR FORMATTED PRINTOUT
NUNIT     = 1 FOR ENG.(DEFAULT), 2 FOR METRIC

SPPRE     =SINGLE SPRING PRELOAD
NOSP      =NUMBER OF SPRINGS
SKXX      =FLUID-FILM STIFFNESS, XX
SKXY      =FLUID-FILM STIFFNESS, XY
SKYX      =FLUID-FILM STIFFNESS, YX
SKYY      =FLUID-FILM STIFFNESS, YY
SKZZ      =FLUID-FILM STIFFNESS, ZZ
SKZB      =FLUID-FILM STIFFNESS, ZB
SKZA      =FLUID-FILM STIFFNESS, ZA
SKBZ      =FLUID-FILM STIFFNESS, BZ
SKBB      =FLUID-FILM STIFFNESS, BB
SKBA      =FLUID-FILM STIFFNESS, BA
SKAZ      =FLUID-FILM STIFFNESS, AZ
SKAB      =FLUID-FILM STIFFNESS, AB
SKAA      =FLUID-FILM STIFFNESS, AA

DYY       =FLUID-FILM DAMPING
DYX       =FLUID-FILM DAMPING
DXY       =FLUID-FILM DAMPING
DXX       =FLUID-FILM DAMPING
DZZ       =FLUID-FILM DAMPING
DZB       =FLUID-FILM DAMPING
DZA       =FLUID-FILM DAMPING
DBZ       =FLUID-FILM DAMPING
DBB       =FLUID-FILM DAMPING
DBA       =FLUID-FILM DAMPING
```

```
DAZ       =FLUID-FILM DAMPING
DAB       =FLUID-FILM DAMPING
DAA       =FLUID-FILM DAMPING
SPRST     =CLOSING SPRING STIFFNESS
FFL       = EQUILIBRIUM FLUID-FILM FORCE
HO        = EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
CO        = RING SEAL CLEARANCE
SKEL      = O-RING STIFFNESS PER UNIT LENGTH
DEL       = O-RING DAMPING PER UNIT LENGTH
SCPREL    = O-RING AND PISTON RING PRELOAD PER UNIT LENGTH

OMEGA     =SHAFT ROTATIONAL SPEED
POD       =OD PRESSURE
PID       =ID PRESSURE
COFSC     =COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC      =FLUID FILM VISCOSITY
DT        =VALUE OF TIME STEP INCREMENT
NTS       =NUMBER OF TIME STEPS
NT        =INITIAL TIME STEP NUMBER

XO        = SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO        = SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO        = SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
BO        = SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
AO        = SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
OMEGAX    = SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
OMEGAY    = SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
OMEGAZ    = SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
OMEGAB    = SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
OMEGAA    = SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S
TINIT     = INITIAL TIME, SEC
CONT      = TRUE IF THE RUN IS A CONTINUATION
SPPRE     =SINGLE SPRING PRELOAD

U(5)      =SEAL DISPLACEMENTS
UDOT(5)   =SEAL VELOCITIES
UDDOT(5)  =SEAL ACCELERATIONS
FRICX     =FRICTION FORCE IN X DIRECTION
FRICY     =FRICTION FORCE IN Y DIRECTION
FRICZ     =FRICTION FORCE IN Z DIRECTION
FRICB     =FRICTION MOMENT ABOUT X-X AXIS
FRICA     =FRICTION MOMENT ABOUT Y-Y AXIS

*GEOMETRY
PISTON            T   = TRUE IF SECONDARY PISTON RING
ZSCO     0.7120      =AXIAL DISTANCE TO SECONDARY SEAL
ROS      1.580       =OUTSIDE RADIUS OF SECONDARY SEAL
RIS      1.240       =INSIDE RADIUS OF SEAL INTERFACE
RSCI     1.220       =PISTON RING INSIDE RADIUS
RSCO     1.400       =PISTON RING OUTSIDE RADIUS
RSP      1.563       =MEAN SPRING RADIUS
NELM     3.000       =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO     0.2525      =AXIAL DISTANCE TO CLOSING SPRINGS
THETO    0.0000E+00  =ANGLE TO FIRST CLOSING SPRING
DTHET    0.5236      =ANGLE BETWEEN SPRINGS,
RIEL(20)  1.025      =INSIDE RADIUS OF ELEMENT
   1.025      1.025      0.0000E+00  0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
```

Figure 17. Sample Problem 1 Output

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```
ROEL(20) =OUTSIDE RADIUS OF ELEMENT
    1.580       1.780       1.220
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
ELEML(20) =ELEMENT LENGTH
0.9250E-01   0.1600      0.6125
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
DENS(20) =ELEMENT DENSITY
    0.2500      0.2500      0.2500
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
ZL(20)   =AXIAL DIST. FROM INTERFACE TO ELEM.
0.0000E+00  0.9250E-01   0.2525
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00

APR   = 0.5360       =UNBALANCED PISTON RING FACE AREA
WPR   = 0.2500E-01   =CIRCUMFERENTIAL PISTON RING WIDTH
*SPRING AND DAMPING
SPPRE = 0.1500       SINGLE SPRING PRELOAD
NOSP  = 12.00        NUMBER OF SPRINGS
SKZZ  = 0.4210E+06   FLUID-FILM STIFFNESS, KZZ
SKZA  = 0.0000E+00   FLUID-FILM STIFFNESS, KZA
SKZB  = 0.0000E+00   FLUID-FILM STIFFNESS, KZB
SKBZ  = 0.0000E+00   FLUID-FILM STIFFNESS, KBZ
SKBB  = 0.3612E+06   FLUID-FILM STIFFNESS, KBB
*SKBA = 0.0
*SKAZ = 0.0
*SKAB = 0.0
SKAA  = 0.3612E+06   FLUID-FILM STIFFNESS, KAA
DZZ   = 0.0000E+00   FLUID-FILM DAMPING
DZB   = 0.0000E+00   FLUID-FILM DAMPING
DZA   = 0.0000E+00   FLUID-FILM DAMPING
DBZ   = 0.0000E+00   FLUID-FILM DAMPING
DBB   = 0.0000E+00   FLUID-FILM DAMPING
DBA   = 0.0000E+00   FLUID-FILM DAMPING
DAZ   = 0.0000E+00   FLUID-FILM DAMPING
DAB   = 0.0000E+00   FLUID-FILM DAMPING
DAA   = 0.0000E+00   FLUID-FILM DAMPING
SPRST = 5.050        CLOSING SPRING STIFFNESS
HO    = 0.1170E-02   EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL   = 2375.        EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA = 7330.        SHAFT ROTATIONAL SPEED
POD   = 750.0        OD PRESSURE
PID   = 0.0000E+00   ID PRESSURE
COFSC = 0.2000       COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC  = 0.1700E-07   FLUID FILM VISCOSITY
DT    = 0.8572E-05   VALUE OF TIME STEP INCREMENT
NTS   = 1000.        NUMBER OF TIME STEPS
NT    = 1.000        INITIAL TIME STEP NUMBER
*INITIAL CONDITIONS
XO    = 0.5000E-03   SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
```

```
YO    = 0.5000E-03   SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO    = 0.5000E-03   SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
AO,
AD.   = 0.5000E-03   SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,R
BO,
AD.   = 0.5000E-03   SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,R
OMEGAX = 7330.       SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS,
RAD/S
OMEGAY = 7330.       SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS,
RAD/S
OMEGAZ = 7330.       SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS,
RAD/S
TINIT = 0.0000E+00   INITIAL TIME, SEC
OMEGAB = 7330.       SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS,
RAD/S
OMEGAA = 7330.       SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS,
RAD/S
1
................................................................

        TOTAL MASS,LB.-SEC**2/IN = 0.1505581E-02
        CG DISTANCE,IN. =    0.2895275
        POLAR MOMENT OF INERTIA,LB-SEC**2-IN = 0.2626893E-02
        TRANSVERSE MOMENT OF INERTIA,LB.-SEC**2-IN =  0.1397172E-02

................................................................

        ACL=CLOSING AREA,IN**2=   3.166725
        FHCL=HYDRAULIC CLOSING FORCE,LBS.=    2375.044
        AIF=INTERFACE AREA,IN**2,=   3.012159
        FIFPRE=INTERFACE PRELOAD,LBS=   2376.844
        SCFRIC=SECONDARY SEAL PRELOAD FRICTION,LBS=    32.98672
        HO=INITIAL FILM THICKNESS OR INTERFERENCE,IN.=  0.1170000E-02

................................................................

        TO CONTINUE THIS CASE READ THE FOLLOWING      VARIABLES IN NAME
```

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Figure 17. Continued

```
03/29/1995  23:40        Filename: SAMPLE1.OUT                              Page  5

LIST CONTIN


NT=    1001
U(1)=   0.5029428E-03      U(2)= -0.2942818E-05      U(3)= -0.2870002E-03
U(4)=   0.6351748E-03      U(5)= -0.1935520E-03
UDOT(1)=   0.0000000E+00      UDOT(2)=   0.0000000E+00
UDOT(3)=   3.434496          UDOT(4)= -0.2241758
UDOT(5)=   4.711916
UDOTT(1)=   0.0000000E+00      UDOTT(2)=   0.0000000E+00
UDOTT(3)=   58354.43          UDOTT(4)= -59312.23
UDOTT(5)=   25723.67
FRICX=  -80.40000             FRICY=   80.40000
FRICZ=  -32.98672            FRICA= -33.99206
FRICB=  -33.99206
```
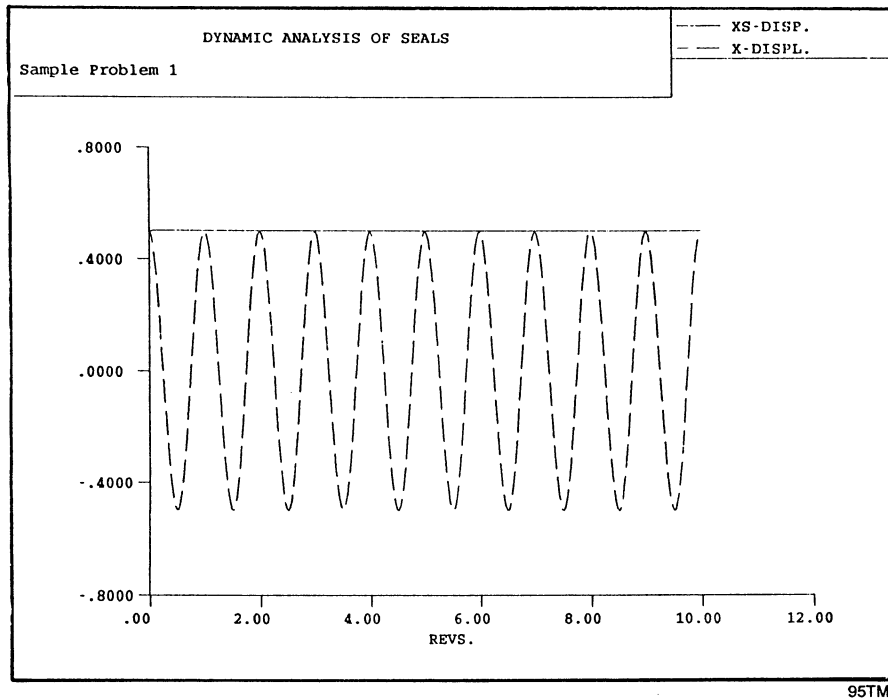
Figure 17. Continued

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Figure 18. x Displacement versus Shaft Revolutions
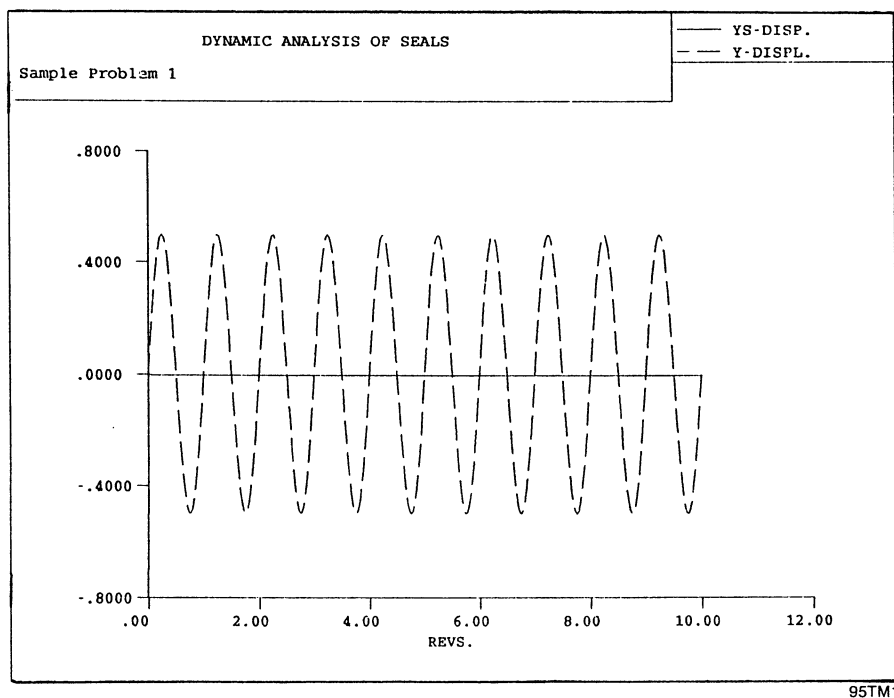

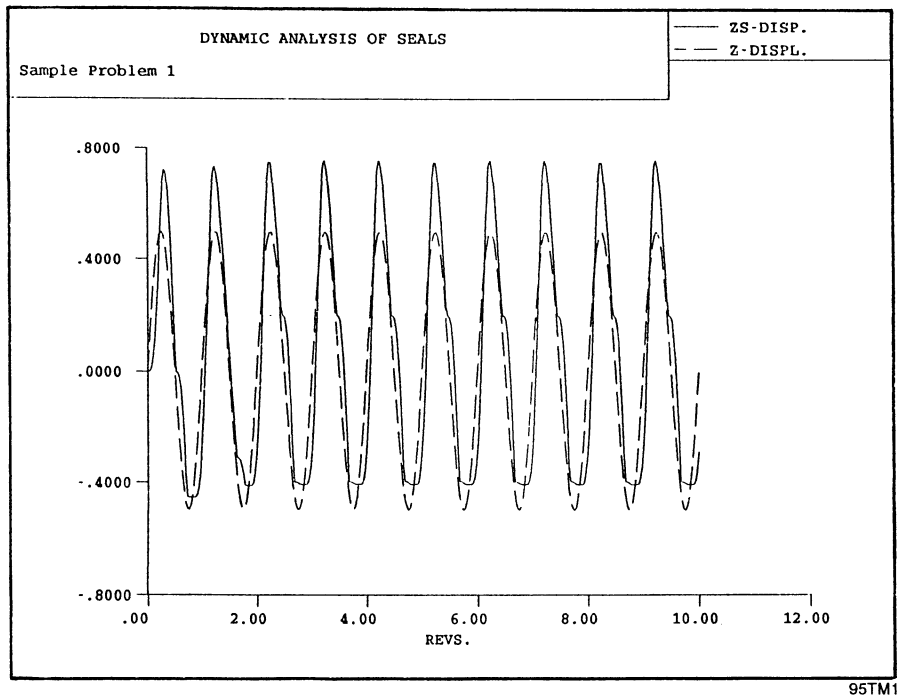Figure 19. y Displacement versus Shaft Revolutions

Figure 20. z Displacement versus Shaft Revolutions
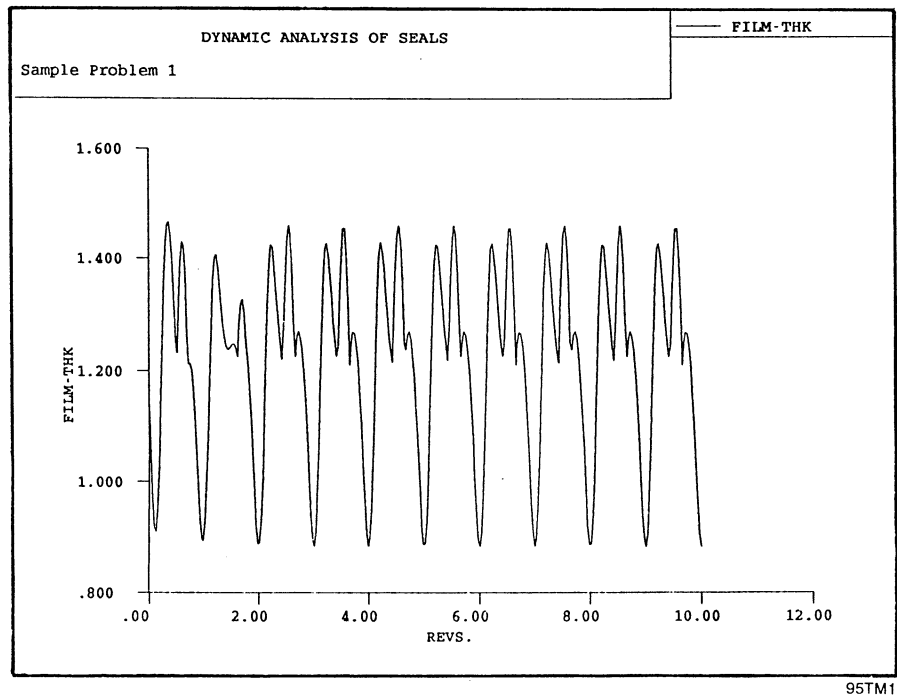
Figure 21. Film Thickness versus Shaft Revolutions
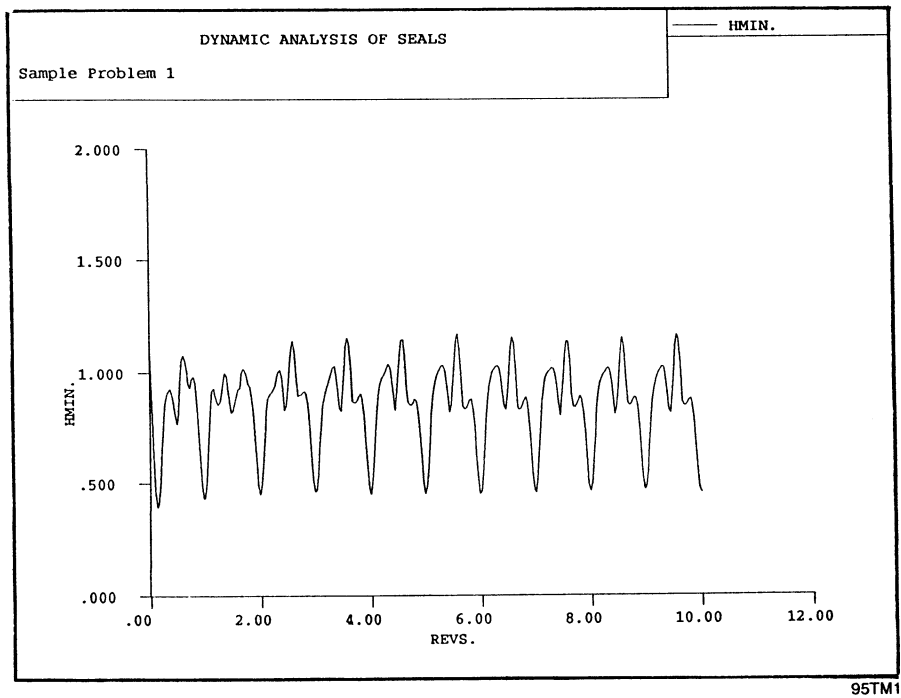
Figure 22. Minimum Film Thickness versus Shaft Revolutions

Figure 23. Rotational Displacement About x Axis versus Shaft Revolutions

Figure 24. Rotational Displacement About y Axis versus Shaft Revolutions

Figure 25. x Friction versus Shaft Revolutions

Figure 26. y Friction versus Shaft Revolutions
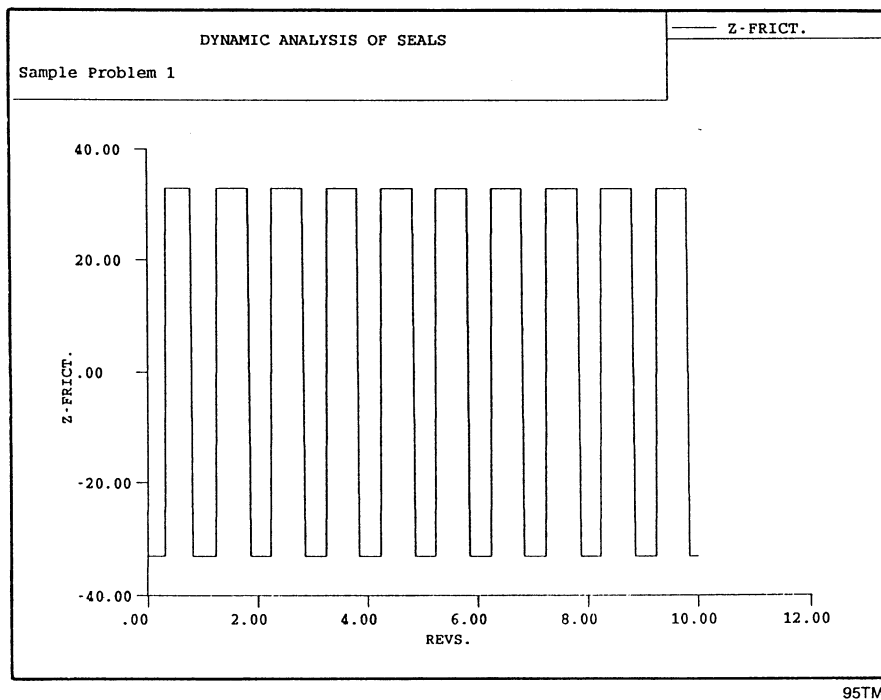
Figure 27. z Friction versus Shaft Revolutions

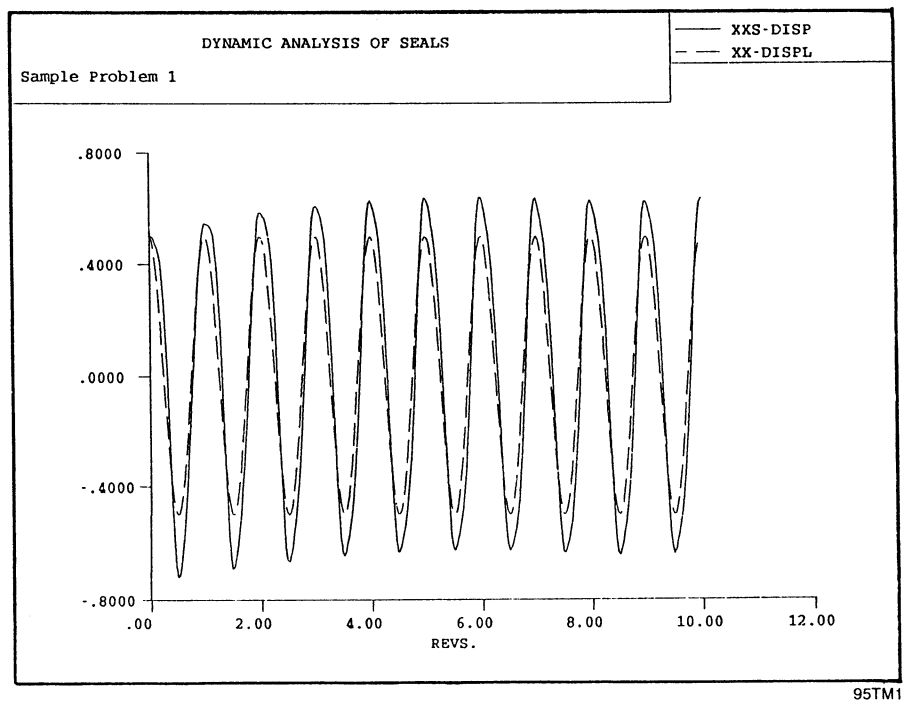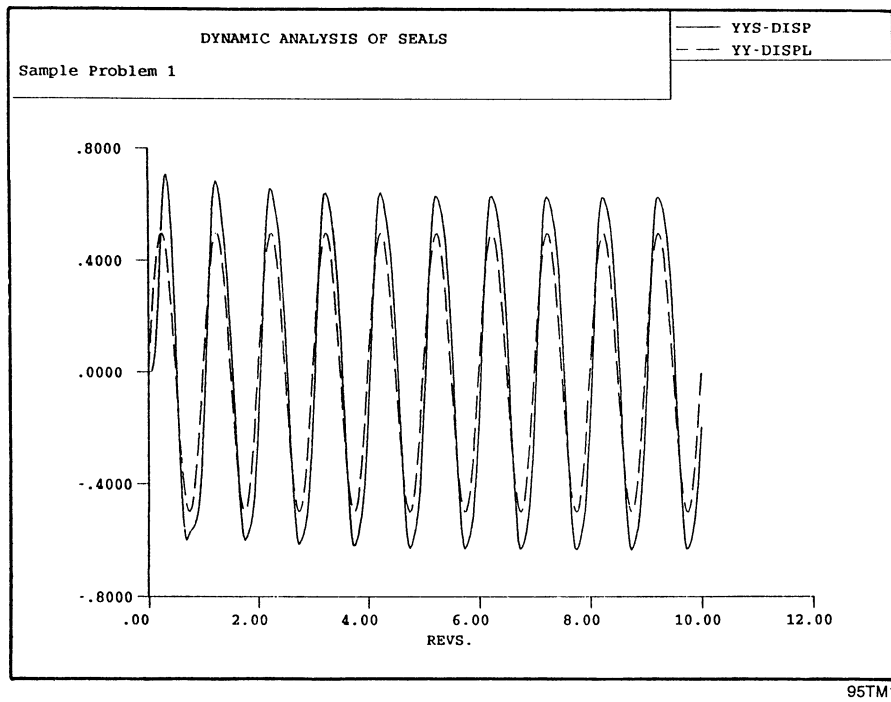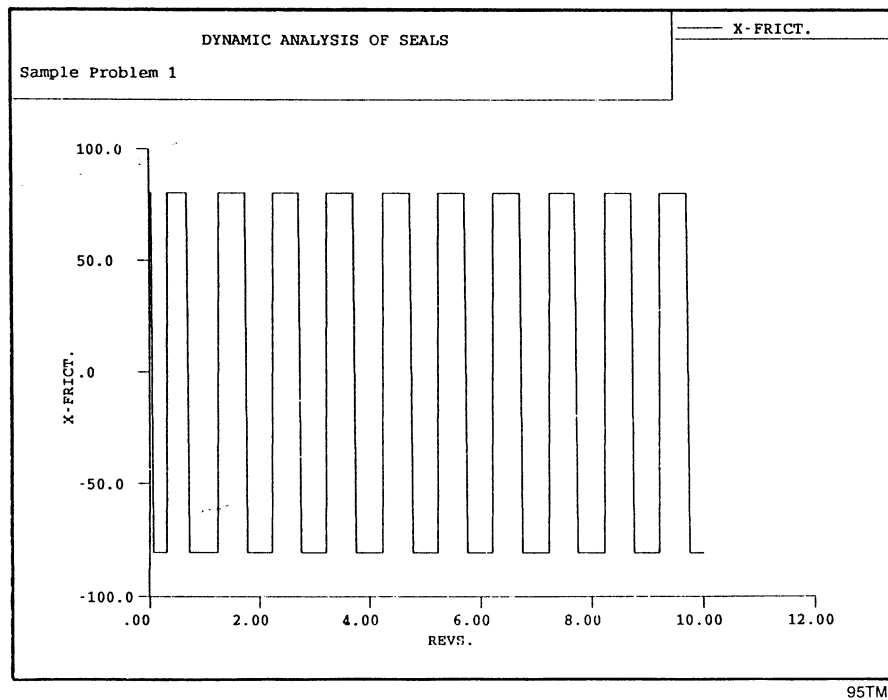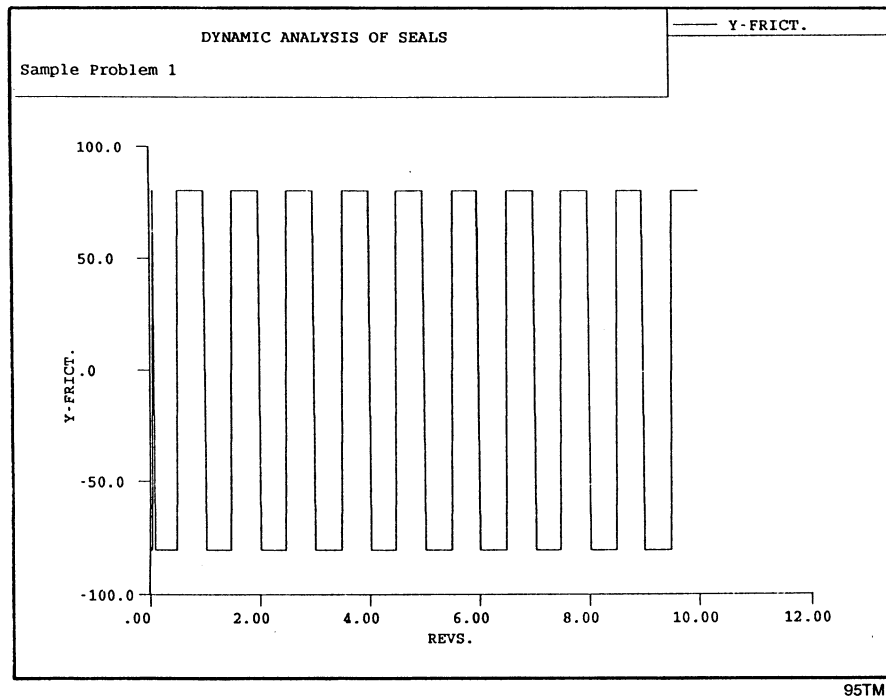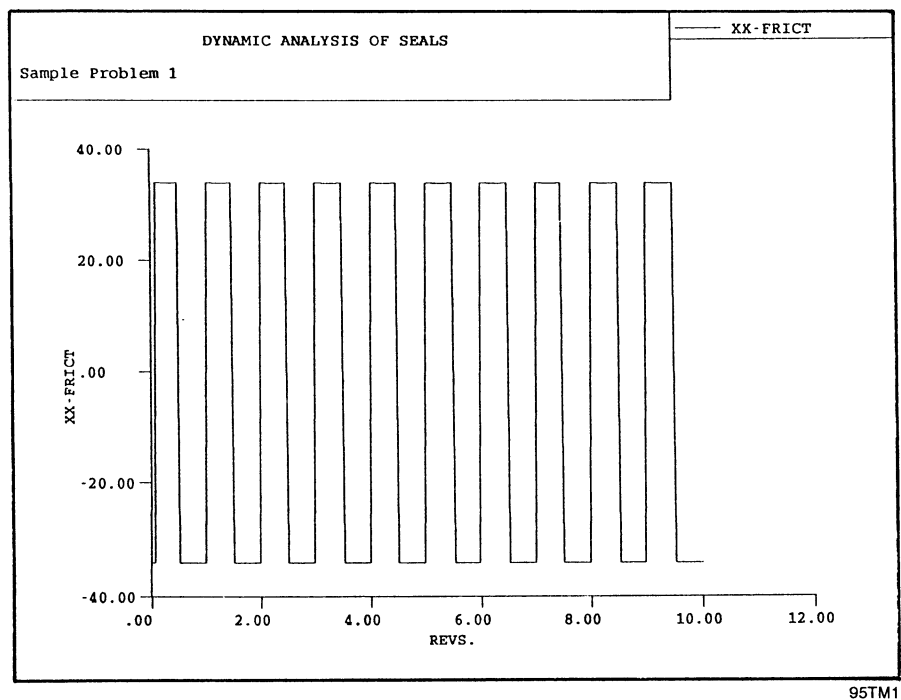Figure 28. Friction Moment About x Axis versus Shaft Revolutions
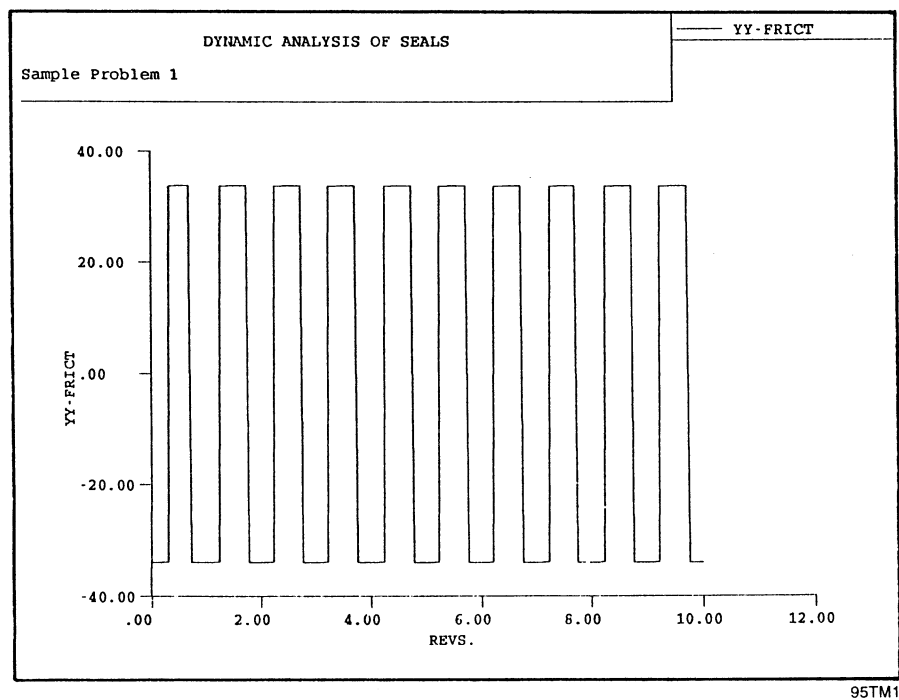
Figure 29. Friction Moment About y Axis versus Shaft Revolutions

```
SAMPLE2
DYSEAL SAMPLE INPUT
*
HELP
*GEOMETRY
PISTON
ZSCO      0.712
ROS       1.58
RIS       1.24
RSCI      1.22
RSCO      1.40
RSP       1.5625
NELM      3
ZSPO      0.2525
THETO     0.0
DTHET     .5236
RIEL(20)  1.025    1.025  1.025
ROEL(20)  1.580    1.780  1.220
ELEML(20) .0925    .1600  .6125
DENS(20)  .250     .250   .250
ZL(20)    0.0  .0925  .2525  .2525
APR       .536
WPR       .025
*SPRING AND DAMPING
SPPRE     .150
NOSP      12
SKZZ      421000.
SKZA      0.0
SKZB      0.0
SKBZ      0.0
SKBB      361239.
*SKBA     0.0
*SKAZ     0.0
*SKAB     0.0
SKAA      361239.
DZZ       0.0
DZB       0.0
DZA       0.0
DBZ       0.0
DBB       0.0
DBA       0.0
DAZ       0.0
DAB       0.0
DAA       0.0
SPRST     5.050
HO        .00117
FFL       2375.0
*OPERATING CONDITIONS
OMEGA     7330.
POD       750.
PID       0.0
COFSC     .2
VISC      1.7E-08
DT        8.571876E-06
NTS       1500
NT        1001
*INITIAL CONDITIONS
XO        .0005
YO        .0005
ZO        .0005
AO        .0005
BO        .0005
OMEGAX    7330.
OMEGAY    7330.
OMEGAZ    7330.
TINIT     0.0
```

```
OMEGAB    7330.
OMEGAA    7330.
CONT      .00050943 -.294282E-05 -.0002870 .000635175 -.000193484
U         0.0 0.0 3.434496 -.2241758 4.713080
UDOT      0.0 0.0 58354.43 -59312.23 25680.82
UDOTT     -80.40000
FRICX     80.40000
FRICY     -32.98672
FRICZ     -33.99206
FRICA     -33.99206
FRICB
END
```

Figure 30. Sample Problem 2 Input

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ECHO OF INPUT

DYSEAL SAMPLE INPUT
*

DYSEAL INPUT INSTRUCTIONS
```
ZSCO      =AXIAL DISTANCE TO SECONDARY SEAL
ROS       =OUTSIDE RADIUS OF SEAL INTERFACE
RIS       =INSIDE RADIUS OF SEAL INTERFACE
RSCI      =PISTON RING INSIDE RADIUS
RSCO      =PISTON RING OUTSIDE RADIUS
RSC       =O-RING SECONDARY SEAL RADIUS
RSP       =MEAN SPRING RADIUS
ZSPO      =AXIAL DISTANCE TO CLOSING SPRINGS
THETO     =ANGLE TO FIRST CLOSING SPRING
DTHET     =ANGLE BETWEEN SPRINGS,
NELM      =NUMBER OF GEOMETRICAL ELEMENTS
RIEL(20)  =INSIDE RADIUS OF ELEMENT
ROEL(20)  =OUTSIDE RADIUS OF ELEMENT
ELEML(20) =ELEMENT LENGTH
DENS(20)  =ELEMENT DENSITY
EMOD      =ELASTIC MODULUS OF RING SEAL
APR       =UNBALANCED PISTON RING FACE AREA
VPR       =CIRCUMFERENTIAL PISTON RING WIDTH
ZL(20)    =AXIAL DIST. FROM INTERFACE TO ELEM.
INSIDE    =1, ID PISTON RING
PISTON    = TRUE IF SECONDARY PISTON RING
ORING     = TRUE IF SECONDARY O-RING
RING      = TRUE FOR A RING SEAL
TOTAL     = TRUE FOR FORMATTED PRINTOUT
NUNIT     = 1 FOR ENG.(DEFAULT), 2 FOR METRIC

SPPRE     =SINGLE SPRING PRELOAD
NOSP      =NUMBER OF SPRINGS
SKXX      =FLUID-FILM STIFFNESS,  KXX
SKXY      =FLUID-FILM STIFFNESS,  KXY
SKYX      =FLUID-FILM STIFFNESS,  KYX
SKYY      =FLUID-FILM STIFFNESS,  KYY
SKZZ      =FLUID-FILM STIFFNESS,  KZZ
SKZB      =FLUID-FILM STIFFNESS,  KZB
SKZA      =FLUID-FILM STIFFNESS,  KZA
SKBZ      =FLUID-FILM STIFFNESS,  KBZ
SKBB      =FLUID-FILM STIFFNESS,  KBB
SKBA      =FLUID-FILM STIFFNESS,  KBA
SKAZ      =FLUID-FILM STIFFNESS,  KAZ
SKAB      =FLUID-FILM STIFFNESS,  KAB
SKAA      =FLUID-FILM STIFFNESS,  KAA

DYY       =FLUID-FILM DAMPING
DYX       =FLUID-FILM DAMPING
DXY       =FLUID-FILM DAMPING
DXX       =FLUID-FILM DAMPING
DZZ       =FLUID-FILM DAMPING
DZB       =FLUID-FILM DAMPING
DZA       =FLUID-FILM DAMPING
DBZ       =FLUID-FILM DAMPING
DBB       =FLUID-FILM DAMPING
DBA       =FLUID-FILM DAMPING
```

```
DAZ       =FLUID-FILM DAMPING
DAB       =FLUID-FILM DAMPING
DAA       =FLUID-FILM DAMPING
SPRST     =CLOSING SPRING STIFFNESS
FFL       = EQUILIBRIUM FLUID-FILM FORCE
HO        = EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
CO        = RING SEAL CLEARANCE
SKEL      = O-RING STIFFNESS PER UNIT LENGTH
DEL       = O-RING DAMPING PER UNIT LENGTH
SCPREL    = O-RING AND PISTON RING PRELOAD PER UNIT LENGTH

OMEGA     =SHAFT ROTATIONAL SPEED
POD       =OD PRESSURE
PID       =ID PRESSURE
COFSC     =COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC      =FLUID FILM VISCOSITY
DT        =VALUE OF TIME STEP INCREMENT
NTS       =NUMBER OF TIME STEPS
NT        =INITIAL TIME STEP NUMBER

XO        = SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO        = SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO        = SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
BO        = SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
AO        = SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
OMEGAX    = SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
OMEGAY    = SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
OMEGAZ    = SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
OMEGAB    = SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
OMEGAA    = SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S
TINIT     = INITIAL TIME, SEC
CONT      = TRUE IF THE RUN IS A CONTINUATION
SPPRE     =SINGLE SPRING PRELOAD

U(5)      =SEAL DISPLACEMENTS
UDOT(5 )  =SEAL VELOCITIES
UDOTT(5)  =SEAL ACCELERATIONS
FRICX     =FRICTION FORCE IN X DIRECTION
FRICY     =FRICTION FORCE IN Y DIRECTION
FRICZ     =FRICTION FORCE IN Z DIRECTION
FRICB     =FRICTION MOMENT ABOUT X-X AXIS
FRICA     =FRICTION MOMENT ABOUT Y-Y AXIS

*GEOMETRY
PISTON                 T   = TRUE IF SECONDARY PISTON RING
ZSCO      0.7120           =AXIAL DISTANCE TO SECONDARY SEAL
ROS       1.580            =OUTSIDE RADIUS OF SECONDARY SEAL
RIS       1.240            =INSIDE RADIUS OF SEAL INTERFACE
RSCI      1.220            =PISTON RING INSIDE RADIUS
RSCO      1.400            =PISTON RING OUTSIDE RADIUS
RSP       1.563            =MEAN SPRING RADIUS
NELM      3.000            =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO      0.2525           =AXIAL DISTANCE TO CLOSING SPRINGS
THETO     0.0000E+00       =ANGLE TO FIRST CLOSING SPRING
DTHET     0.5236           =ANGLE BETWEEN SPRINGS,
RIEL(20)  =INSIDE RADIUS OF ELEMENT
     1.025       1.025       0.0000E+00  0.0000E+00  0.0000E+00
   0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
   0.0000E+00  0.0000E+00  0.0000E+00
```

Figure 31. Sample Problem 2 Output

95TM1

95TM1

```
03/29/1995  23:34      Filename: SAMPLE2.OUT                                              Page  4

YO       = 0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION

ZO       = 0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION

AO       = 0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,R
AD.
BO       = 0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,R
AD.
OMEGAX   = 7330.         SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS,
RAD/S
OMEGAY   = 7330.         SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS,
RAD/S
OMEGAZ   = 7330.         SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS,
RAD/S
TINIT    = 0.0000E+00    INITIAL TIME, SEC

OMEGAB   = 7330.         SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS,
RAD/S
OMEGAA   = 7330.         SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS,
RAD/S
CONT     = T             TRUE IF THE RUN IS A CONTINUATION

               SEAL DISPLACEMENTS
U(5)    0.5029E-03 -0.2943E-05 -0.2870E-03  0.6352E-03 -0.1935E-03  0.0000E+00
               SEAL VELOCITIES
UDOT(5) =  0.0000E+00    3.434       -0.2242      4.713      0.0000E+00
               SEAL ACCELERATIONS
UDOTT(5) = 0.0000E+00  0.0000E+00  0.5835E+05 -0.5931E+05  0.2568E-05  0.0000E+00
FRICX = -80.40          FRICTION FORCE IN X DIRECTION
FRICY =  80.40          FRICTION FORCE IN Y DIRECTION
FRICZ = -32.99          FRICTION FORCE IN Z DIRECTION
FRICA = -33.99          FRICTION MOMENT ABOUT Y-Y AXIS
FRICB = -33.99          FRICTION MOMENT ABOUT X-X AXIS
1

       TOTAL MASS,LB.-SEC**2/IN =   0.1505581E-02

       CG DISTANCE,IN. =       0.289275

       POLAR MOMENT OF INERTIA,LB-SEC**2-IN =   0.2626893E-02

       TRANSVERSE MOMENT OF INERTIA,LB.-SEC**2-IN =   0.1397172E-02


       ACL=CLOSING AREA,IN**2=    3.166725

       FHCL=HYDRAULIC CLOSING FORCE,LBS.=    2375.044

       AIF=INTERFACE AREA,IN**2,=  3.012159

       FIPRE=INTERFACE PRELOAD,LBS=  2376.844

       SCFRIC=SECONDARY SEAL PRELOAD FRICTION,LBS=   32.98672

       HO=INITIAL FILM THICKNESS OR INTERFERENCE,IN.=  0.1170000E-02
```

```
03/29/1995  23:34      Filename: SAMPLE2.OUT                                              Page  3

ROEL(20)   =OUTSIDE RADIUS OF ELEMENT
  1.580      1.780      1.220      0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
ELEML(20)  =ELEMENT LENGTH
  0.9250E-01 0.1600     0.6125     0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
DENS(20)   =ELEMENT DENSITY
  0.2500     0.2500     0.2500     0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
ZL(20)     =AXIAL DIST. FROM INTERFACE TO ELEM.
  0.0000E+00 0.9250E-01 0.2525     0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
APR   = 0.5360        =UNBALANCED PISTON RING FACE AREA
WPR   = 0.2500E-01    =CIRCUMFERENTIAL PISTON RING WIDTH
*SPRING AND DAMPING
SPPRE = 0.1500        SINGLE SPRING PRELOAD
NOSP  = 12.500        NUMBER OF SPRINGS
SKZZ  = 0.4210E+06    FLUID-FILM STIFFNESS, KZZ
SKZA  = 0.0000E+00    FLUID-FILM STIFFNESS, KZA
SKZB  = 0.0000E+00    FLUID-FILM STIFFNESS, KZB
SKBZ  = 0.0000E+00    FLUID-FILM STIFFNESS, KBZ
SKBB  = 0.3612E+06    FLUID-FILM STIFFNESS, KBB
*SKBA = 0.0
*SKAZ = 0.0
*SKAB = 0.0
SKAA  = 0.3612E+06    FLUID-FILM STIFFNESS, KAA
DZZ   = 0.0000E+00    FLUID-FILM DAMPING
DZB   = 0.0000E+00    FLUID-FILM DAMPING
DZA   = 0.0000E+00    FLUID-FILM DAMPING
DBZ   = 0.0000E+00    FLUID-FILM DAMPING
DBB   = 0.0000E+00    FLUID-FILM DAMPING
DBA   = 0.0000E+00    FLUID-FILM DAMPING
DAZ   = 0.0000E+00    FLUID-FILM DAMPING
DAB   = 0.0000E+00    FLUID-FILM DAMPING
DAA   = 0.0000E+00    FLUID-FILM DAMPING
SPRST = 5.050         CLOSING SPRING STIFFNESS
HO    = 0.1170E-02    EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL   = 2375.         EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA = 7330.         SHAFT ROTATIONAL SPEED
P0O   = 750.0         OD PRESSURE
PID   = 0.0000E+00    ID PRESSURE
COFSC = 0.2000        COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC  = 0.1700E-07    FLUID FILM VISCOSITY
DT    = 0.8572E-05    VALUE OF TIME STEP INCREMENT
NTS   = 1500.         NUMBER OF TIME STEPS
NT    = 1001.         INITIAL TIME STEP NUMBER
*INITIAL CONDITIONS
XO    = 0.5000E-03        SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
```

Figure 31. Continued

....
1 ....
....

LIST CONTIN

TO CONTINUE THIS CASE READ THE FOLLOWING   VARIABLES IN NAME

NT= 1501
U(1)= 0.5029430E-03   U(2)= -0.2942820E-05   U(3)= -0.2870006E-03
U(4)= 0.6326006E-03   U(5)= -0.1928418E-03
UDOT(1)= 0.0000000E+00   UDOT(2)= 0.0000000E+00
UDOT(3)= 3.434486   UDOT(4)= -0.2195411
UDOT(5)= 4.707608
UDOTT(1)= 0.0000000E+00   UDOTT(2)= 0.0000000E+00
UDOTT(3)= 58354.42   UDOTT(4)= -58646.52
UDOTT(5)= 25539.89
FRICX= -80.40000   FRICY= 80.40000
FRIC2= -32.98672   FRICA= -33.99206
FRICB= -33.99206

....

Figure 31. Continued

95TM1
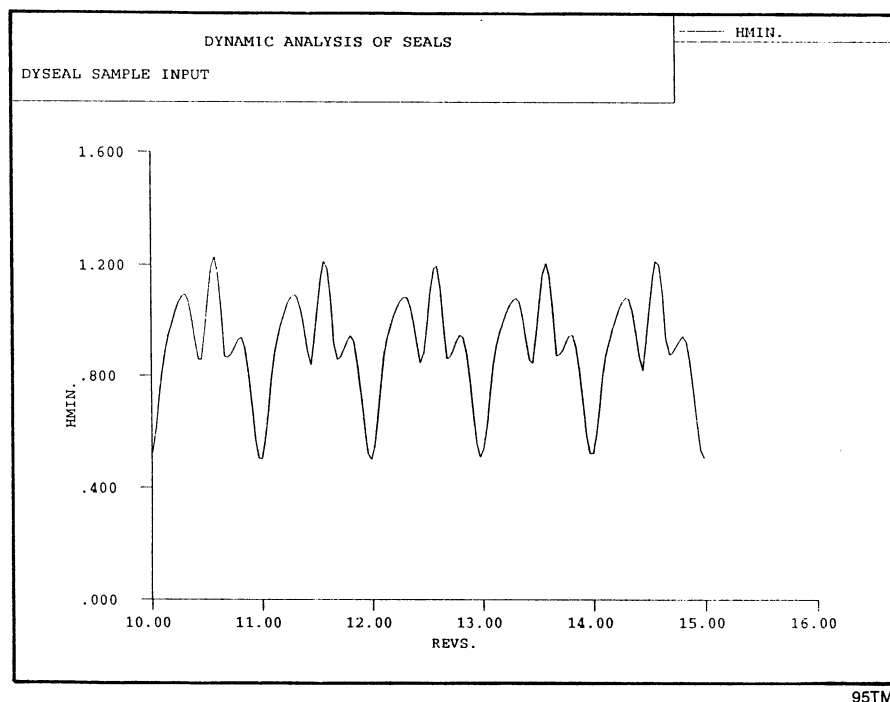
Figure 32. Sample Problem 2 Minimum Film Thickness versus Shaft Revolutions

```
SAMPLE3
DYSEAL SAMPLE3 INPUT
*
*GEOMETRY
PISTON
TOTAL
ZSCO        0.712
ROS         1.58
RIS         1.24
RSCI        1.22
RSCO        1.40
RSP         1.5625
NELM        3
ZSPO        0.2525
THETO       0.0
DTHET       .5236
RIEL(20)    1.025   1.025
ROEL(20)    1.580   1.780   1.220
ELEML(20)   .0925   .1600   .6125
DENS(20)    .250    .250    .250
ZL(20)      0.0     .0925   .2525
APR         .536
WPR         .025
*SPRING AND DAMPING
SPPRE       .150
NOSP        12
SKZZ        421000.
SKZA        0.0
SKZB        0.0
SKBZ        0.0
SKBB        361239.
*SKBA       0.0
*SKAZ       0.0
*SKAB       0.0
SKAA        361239.
DZZ         0.0
DZB         0.0
DZA         0.0
DBZ         0.0
DBB         0.0
DBA         0.0
DAZ         0.0
DAB         0.0
DAA         0.0
SPRST       5.050
HO          .00117
FFL         2375.0
*OPERATING CONDITIONS
OMEGA       7330.
POD         750.
PID         0.0
COFSC       .2
VISC        1.7E-08
DT          8.571876E-06
NTS         50
NT          1
*INITIAL CONDITIONS
XO          .0005
YO          .0005
ZO          .0005
AO          .0005
BO          .0005
OMEGAX      7330.
OMEGAY      7330.
OMEGAZ      7330.
TINIT       0.0
```

```
OMEGAB      7330.
OMEGAA      7330.
END
```

95TM1

Figure 33. Sample Problem 3 Input (Formatted Output)

ECHO OF INPUT

DYSEAL SAMPLE3 INPUT
*
*GEOMETRY

PISTON	T	= TRUE IF SECONDARY PISTON RING
TOTAL	T	= TRUE FOR FORMATTED PRINTOUT
ZSCO	0.7120	=AXIAL DISTANCE TO SECONDARY SEAL
ROS	1.580	=OUTSIDE RADIUS OF SEAL INTERFACE
RIS	1.240	=INSIDE RADIUS OF SEAL INTERFACE
RSCI	1.220	=PISTON RING INSIDE RADIUS
RSCO	1.400	=PISTON RING OUTSIDE RADIUS
RSP	1.563	=MEAN SPRING RADIUS
NELM	3.000	=NUMBER OF GEOMETRICAL ELEMENTS
ZSPO	0.2525	=AXIAL DISTANCE TO CLOSING SPRINGS
THETO	0.0000E+00	=ANGLE TO FIRST CLOSING SPRING
DTHET	0.5236	=ANGLE BETWEEN SPRINGS,

RIEL(20) =INSIDE RADIUS OF ELEMENT
```
  1.025      1.025      1.025      0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
```

ROEL(20) =OUTSIDE RADIUS OF ELEMENT
```
  1.580      1.780      1.220      0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
```

ELEML(20) =ELEMENT LENGTH
```
  0.9250E-01 0.1600     0.6125     0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
```

DENS(20) =ELEMENT DENSITY
```
  0.2500     0.2500     0.2500     0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
```

ZL(20) =AXIAL DIST. FROM INTERFACE TO ELEM.
```
  0.0000E+00 0.9250E-01 0.2525     0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00
```

| APR | 0.5360 | =UNBALANCED PISTON RING FACE AREA |

Figure 34. Sample Problem 3 (Formatted Output)

95TM1

```
WPR          0.2500E-01   =CIRCUMFERENTIAL PISTON RING WIDTH
*SPRING AND DAMPING
SPPRE     =  0.1500        SINGLE SPRING PRELOAD
NOSP      =  12.00         NUMBER OF SPRINGS
SKZZ      =  0.4210E+06    FLUID-FILM STIFFNESS, KZZ
SKZA      =  0.0000E+00    FLUID-FILM STIFFNESS, KZA
SKZB      =  0.0000E+00    FLUID-FILM STIFFNESS, KZB
SKBZ      =  0.0000E+00    FLUID-FILM STIFFNESS, KBZ
SKBB      =  0.3612E+06    FLUID-FILM STIFFNESS, KBB
*SKBA     =  0.0
*SKAZ     =  0.0
*SKAB     =  0.0
SKAA      =  0.3612E+06    FLUID-FILM STIFFNESS, KAA
DZZ       =  0.0000E+00    FLUID-FILM DAMPING
DZB       =  0.0000E+00    FLUID-FILM DAMPING
DZA       =  0.0000E+00    FLUID-FILM DAMPING
DBZ       =  0.0000E+00    FLUID-FILM DAMPING
DBB       =  0.0000E+00    FLUID-FILM DAMPING
DBA       =  0.0000E+00    FLUID-FILM DAMPING
DAZ       =  0.0000E+00    FLUID-FILM DAMPING
DAB       =  0.0000E+00    FLUID-FILM DAMPING
DAA       =  0.0000E+00    FLUID-FILM DAMPING
SPRST     =  5.050         CLOSING SPRING STIFFNESS
HO        =  0.1170E-02    EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL       =  2375.         EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA     =  7330.         SHAFT ROTATIONAL SPEED
POO       =  750.0         OD PRESSURE
PID       =  0.0000E+00    ID PRESSURE
COFSC     =  0.2000        COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC      =  0.1700E-07    FLUID FILM VISCOSITY
DT        =  0.8572E-05    VALUE OF TIME STEP INCREMENT
NTS       =  50.00         NUMBER OF TIME STEPS
NT        =  1.000         INITIAL TIME STEP NUMBER
*INITIAL CONDITIONS
XO        =  0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO        =  0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO        =  0.5000E-03    SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
AO        =  0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
BO        =  0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
OMEGAX    =  7330.         SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
OMEGAY    =  7330.         SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
OMEGAZ    =  7330.         SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
TINIT     =  0.0000E+00    INITIAL TIME, SEC
OMEGAB    =  7330.         SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
```

95TM1

Figure 34. Continued

```
OMEGAA  =  7330.          SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S

1 ...................................................................


          TOTAL MASS,LB.-SEC**2/IN =  0.1505581E-02

          CG DISTANCE,IN. =   0.2895275

          POLAR MOMENT OF INERTIA,LB-SEC**2-IN =  0.2626893E-02

          TRANSVERSE MOMENT OF INERTIA,LB.-SEC**2-IN =  0.1397172E-02


.......................................................................


ACL=CLOSING AREA,IN**2=   3.166725

FHCL=HYDRAULIC CLOSING FORCE,LBS.=   2375.044

AIF=INTERFACE AREA,IN**2,=   3.012159

FIPRE=INTERFACE PRELOAD,LBS=  2376.844

SCFRIC=SECONDARY SEAL PRELOAD FRICTION,LBS=   32.98672

HO=INITIAL FILM THICKNESS OR INTERFERENCE,IN.=  0.1170000E-02


.......................................................................

.......................................................................
```

Figure 34. Continued

SEAL MOTIONS, AND CLEARANCE, MILS AND MILLI-RADIANS

STEP	TIME	REVS	X-DISPL.	Y-DISPL.	Z-DISPL.	XX-DISPL.	YY-DISPL.	FILM-THK.
1	0.00001	0.01000	0.50000	0.00000	0.00000	0.50000	0.00000	1.13860
2	0.00002	0.02000	0.50000	0.00000	0.00000	0.50000	0.00000	1.10733
3	0.00003	0.03000	0.50000	0.00000	0.00008	0.50000	0.00000	1.07639
4	0.00003	0.04000	0.50000	0.00000	0.00055	0.50000	0.00000	1.04620
5	0.00004	0.05000	0.50098	-0.00098	0.00194	0.49944	0.00029	1.01743
6	0.00005	0.06000	0.50294	-0.00294	0.00485	0.49716	0.00156	0.99079
7	0.00006	0.07000	0.50294	-0.00294	0.00982	0.49248	0.00451	0.96693
8	0.00007	0.08000	0.50294	-0.00294	0.01733	0.48614	0.00962	0.94645
9	0.00008	0.09000	0.50294	-0.00294	0.02780	0.47977	0.01731	0.92989
10	0.00009	0.10000	0.50294	-0.00294	0.04158	0.47409	0.02796	0.91769
11	0.00009	0.11000	0.50294	-0.00294	0.05891	0.46885	0.04186	0.91019
12	0.00010	0.12000	0.50294	-0.00294	0.07993	0.46381	0.05921	0.90766
13	0.00011	0.13000	0.50294	-0.00294	0.10472	0.45865	0.08012	0.91023
14	0.00012	0.14000	0.50294	-0.00294	0.13320	0.45306	0.10463	0.91794
15	0.00013	0.15000	0.50294	-0.00294	0.16522	0.44671	0.13265	0.93072
16	0.00014	0.16000	0.50294	-0.00294	0.20053	0.43923	0.16404	0.94837
17	0.00015	0.17000	0.50294	-0.00294	0.23876	0.43029	0.19851	0.97060
18	0.00015	0.18000	0.50294	-0.00294	0.27945	0.41953	0.23574	0.99703
19	0.00016	0.19000	0.50294	-0.00294	0.32206	0.40664	0.27527	1.02717
20	0.00017	0.20000	0.50294	-0.00294	0.36598	0.39131	0.31660	1.06046
21	0.00018	0.21000	0.50294	-0.00294	0.41053	0.37328	0.35915	1.09624
22	0.00019	0.22000	0.50294	-0.00294	0.45498	0.35231	0.40228	1.13383
23	0.00020	0.23000	0.50294	-0.00294	0.49855	0.32823	0.44530	1.17249
24	0.00021	0.24000	0.50294	-0.00294	0.54045	0.30090	0.48750	1.21144
25	0.00021	0.25000	0.50294	-0.00294	0.57990	0.27024	0.52813	1.24990
26	0.00022	0.26000	0.50294	-0.00294	0.61610	0.23625	0.56643	1.28709
27	0.00023	0.27000	0.50294	-0.00294	0.64829	0.19898	0.60168	1.32224
28	0.00024	0.28000	0.50294	-0.00294	0.67576	0.15853	0.63314	1.35462
29	0.00025	0.29000	0.50294	-0.00294	0.69784	0.11510	0.66013	1.38355
30	0.00026	0.30000	0.50294	-0.00294	0.71394	0.06891	0.68201	1.40841
31	0.00027	0.31000	0.50294	-0.00294	0.72356	0.02027	0.69820	1.42867
32	0.00027	0.32000	0.50294	-0.00294	0.72627	-0.03045	0.70819	1.44386
33	0.00028	0.33000	0.50294	-0.00294	0.72257	-0.08284	0.71156	1.45442
34	0.00029	0.34000	0.50294	-0.00294	0.71385	-0.13644	0.70886	1.46169
35	0.00030	0.35000	0.50294	-0.00294	0.70076	-0.19074	0.70162	1.46625
36	0.00031	0.36000	0.50294	-0.00294	0.68321	-0.24522	0.69052	1.46795
37	0.00032	0.37000	0.50294	-0.00294	0.66115	-0.29930	0.67542	1.46667
38	0.00033	0.38000	0.50294	-0.00294	0.63463	-0.35241	0.65620	1.46235

Figure 34. Continued

39	0.00033	0.39000	0.50294	-0.00294	0.60372	-0.40397	0.63282	1.45501
40	0.00034	0.40000	0.50294	-0.00294	0.56858	-0.45339	0.60526	1.44468
41	0.00035	0.41000	0.50294	-0.00294	0.52941	-0.50010	0.57358	1.43150
42	0.00036	0.42000	0.50294	-0.00294	0.48650	-0.54355	0.53789	1.41562
43	0.00037	0.43000	0.50294	-0.00294	0.44016	-0.58322	0.49836	1.39727
44	0.00038	0.44000	0.50294	-0.00294	0.39077	-0.61864	0.45519	1.37671
45	0.00039	0.45000	0.50294	-0.00294	0.33876	-0.64936	0.40867	1.35425
46	0.00039	0.46000	0.50294	-0.00294	0.28457	-0.67500	0.35912	1.33022
47	0.00040	0.47000	0.50294	-0.00294	0.22871	-0.69525	0.30690	1.30502
48	0.00041	0.48000	0.50294	-0.00294	0.17168	-0.70985	0.25242	1.27902
49	0.00042	0.49000	0.50294	-0.00294	0.11403	-0.71863	0.19613	1.25264
50	0.00043	0.50000	0.50294	-0.00294	0.05629	-0.72146	0.13851	1.22629

Figure 34. Continued

SHAFT MOTIONS, MILS AND MILLI-RADIANS

STEP	TIME	REVS	X-DISPL.	Y-DISPL.	Z-DISPL	XX-DISPL.	YY-DISPL.	HMIN
1	0.00001	0.01000	0.49901	0.03140	0.03140	0.49901	0.03140	1.08900
2	0.00002	0.02000	0.49606	0.06267	0.06267	0.49606	0.06267	1.00815
3	0.00003	0.03000	0.49114	0.09369	0.09369	0.49114	0.09369	0.92770
4	0.00003	0.04000	0.48429	0.12434	0.12434	0.48429	0.12434	0.84832
5	0.00004	0.05000	0.47553	0.15451	0.15451	0.47553	0.15451	0.77090
6	0.00005	0.06000	0.46489	0.18406	0.18406	0.46489	0.18406	0.69797
7	0.00006	0.07000	0.45241	0.21289	0.21289	0.45241	0.21289	0.63170
8	0.00007	0.08000	0.43815	0.24088	0.24088	0.43815	0.24088	0.57345
9	0.00008	0.09000	0.42216	0.26791	0.26791	0.42216	0.26791	0.52387
10	0.00009	0.10000	0.40451	0.29389	0.29389	0.40451	0.29389	0.48338
11	0.00009	0.11000	0.38526	0.31871	0.31871	0.38526	0.31871	0.45349
12	0.00010	0.12000	0.36448	0.34227	0.34227	0.36448	0.34227	0.43371
13	0.00011	0.13000	0.34227	0.36448	0.36448	0.34227	0.36448	0.42514
14	0.00012	0.14000	0.31871	0.38526	0.38526	0.31871	0.38526	0.42638
15	0.00013	0.15000	0.29389	0.40451	0.40451	0.29389	0.40451	0.43801
16	0.00014	0.16000	0.26791	0.42216	0.42216	0.26791	0.42216	0.45903
17	0.00015	0.17000	0.24088	0.43815	0.43815	0.24088	0.43815	0.48819
18	0.00015	0.18000	0.21289	0.45241	0.45241	0.21289	0.45241	0.52409
19	0.00016	0.19000	0.18406	0.46489	0.46489	0.18406	0.46489	0.56520
20	0.00017	0.20000	0.15451	0.47553	0.47553	0.15451	0.47553	0.60994
21	0.00018	0.21000	0.12434	0.48429	0.48429	0.12434	0.48429	0.65622
22	0.00019	0.22000	0.09369	0.49114	0.49114	0.09369	0.49114	0.70183
23	0.00020	0.23000	0.06267	0.49606	0.49606	0.06267	0.49606	0.74535
24	0.00021	0.24000	0.03140	0.49901	0.49901	0.03140	0.49901	0.78563
25	0.00021	0.25000	0.00000	0.50000	0.50000	0.00000	0.50000	0.82067
26	0.00022	0.26000	-0.03140	0.49901	0.49901	-0.03140	0.49901	0.85104
27	0.00023	0.27000	-0.06267	0.49606	0.49606	-0.06267	0.49606	0.87669
28	0.00024	0.28000	-0.09369	0.49114	0.49114	-0.09369	0.49114	0.89731
29	0.00025	0.29000	-0.12434	0.48429	0.48429	-0.12434	0.48429	0.91429
30	0.00026	0.30000	-0.15451	0.47553	0.47553	-0.15451	0.47553	0.92812
31	0.00027	0.31000	-0.18406	0.46489	0.46489	-0.18406	0.46489	0.93876
32	0.00027	0.32000	-0.21289	0.45241	0.45241	-0.21289	0.45241	0.94748
33	0.00028	0.33000	-0.24088	0.43815	0.43815	-0.24088	0.43815	0.95547
34	0.00029	0.34000	-0.26791	0.42216	0.42216	-0.26791	0.42216	0.96336
35	0.00030	0.35000	-0.29389	0.40451	0.40451	-0.29389	0.40451	0.96939
36	0.00031	0.36000	-0.31871	0.38526	0.38526	-0.31871	0.38526	0.97201
37	0.00032	0.37000	-0.34227	0.36448	0.36448	-0.34227	0.36448	0.97107
38	0.00033	0.38000	-0.36448	0.34227	0.34227	-0.36448	0.34227	0.96635
39	0.00033	0.39000	-0.38526	0.31871	0.31871	-0.38526	0.31871	0.95803
40	0.00034	0.40000	-0.40451	0.29389	0.29389	-0.40451	0.29389	0.94679
41	0.00035	0.41000	-0.42216	0.26791	0.26791	-0.42216	0.26791	0.93313

Figure 34. Continued

42	0.00036	0.42000	-0.43815	0.24088	0.24088	-0.43815	0.24088	0.91768
43	0.00037	0.43000	-0.45241	0.21289	0.21289	-0.45241	0.21289	0.90115
44	0.00038	0.44000	-0.46489	0.18406	0.18406	-0.46489	0.18406	0.88426
45	0.00039	0.45000	-0.47553	0.15451	0.15451	-0.47553	0.15451	0.86776
46	0.00039	0.46000	-0.48429	0.12434	0.12434	-0.48429	0.12434	0.85238
47	0.00040	0.47000	-0.49114	0.09369	0.09369	-0.49114	0.09369	0.83878
48	0.00041	0.48000	-0.49606	0.06267	0.06267	-0.49606	0.06267	0.82753
49	0.00042	0.49000	-0.49901	0.03140	0.03140	-0.49901	0.03140	0.81910
50	0.00043	0.50000	-0.50000	0.00000	0.00000	-0.50000	0.00000	0.81385

Figure 34. Continued

FRICTION AND INTERFACE FORCES

STEP	TIME	REVS.	X-FRICT	Y-FRICT	Z-FRICT	XX-FRICT	YY-FRICT
1	0.00001	0.01000	80.40000	-80.40000	-32.98672	-33.96679	-33.96679
2	0.00002	0.02000	80.40000	-80.40000	-32.98672	-33.96679	-33.96679
3	0.00003	0.03000	80.40000	-80.40000	-32.98672	-33.96679	-33.96679
4	0.00003	0.04000	80.40000	-80.40000	-32.98672	-33.96678	-33.96678
5	0.00004	0.05000	80.40000	-80.40000	-32.98672	-33.96675	-33.96675
6	0.00005	0.06000	-80.40000	80.40000	-32.98672	-33.96664	-33.96664
7	0.00006	0.07000	-80.40000	80.40000	-32.98672	-33.96640	-33.96640
8	0.00007	0.08000	-80.40000	-80.40000	-32.98672	33.96600	-33.96600
9	0.00008	0.09000	-80.40000	-80.40000	-32.98672	33.96540	-33.96540
10	0.00009	0.10000	-80.40000	-80.40000	-32.98672	33.96456	-33.96456
11	0.00009	0.11000	-80.40000	-80.40000	-32.98672	33.96345	-33.96345
12	0.00010	0.12000	-80.40000	-80.40000	-32.98672	33.96206	-33.96206
13	0.00011	0.13000	-80.40000	-80.40000	-32.98672	33.96036	-33.96036
14	0.00012	0.14000	-80.40000	-80.40000	-32.98672	33.95837	-33.95837
15	0.00013	0.15000	-80.40000	-80.40000	-32.98672	33.95608	-33.95608
16	0.00014	0.16000	-80.40000	-80.40000	-32.98672	33.95351	-33.95351
17	0.00015	0.17000	-80.40000	-80.40000	-32.98672	33.95067	-33.95067
18	0.00015	0.18000	-80.40000	-80.40000	-32.98672	33.94760	-33.94760
19	0.00016	0.19000	-80.40000	-80.40000	-32.98672	33.94432	-33.94432
20	0.00017	0.20000	-80.40000	-80.40000	-32.98672	33.94090	-33.94090
21	0.00018	0.21000	-80.40000	-80.40000	-32.98672	33.93737	-33.93737
22	0.00019	0.22000	-80.40000	-80.40000	-32.98672	33.93378	-33.93378
23	0.00020	0.23000	-80.40000	-80.40000	-32.98672	33.93021	-33.93021
24	0.00021	0.24000	-80.40000	-80.40000	-32.98672	33.92671	-33.92671
25	0.00021	0.25000	-80.40000	-80.40000	-32.98672	33.92334	-33.92334
26	0.00022	0.26000	-80.40000	-80.40000	-32.98672	33.92017	-33.92017
27	0.00023	0.27000	-80.40000	-80.40000	-32.98672	33.91726	-33.91726
28	0.00024	0.28000	-80.40000	-80.40000	-32.98672	33.91467	-33.91467
29	0.00025	0.29000	-80.40000	-80.40000	-32.98672	33.91246	-33.91246
30	0.00026	0.30000	-80.40000	-80.40000	-32.98672	33.91068	-33.91068
31	0.00027	0.31000	-80.40000	-80.40000	-32.98672	33.90939	-33.90939

Figure 34. Continued

32	0.00027	0.32000	-80.40000	-80.40000	-32.98672	-33.90862
33	0.00028	0.33000	-80.40000	-80.40000	32.98672	-33.90840
34	0.00029	0.34000	-80.40000	80.40000	32.98672	-33.90870
35	0.00030	0.35000	-80.40000	80.40000	32.98672	33.90940
36	0.00031	0.36000	-80.40000	80.40000	32.98672	33.91045
37	0.00032	0.37000	-80.40000	80.40000	32.98672	33.91186
38	0.00033	0.38000	-80.40000	80.40000	32.98672	33.91363
39	0.00033	0.39000	-80.40000	80.40000	32.98672	33.91577
40	0.00034	0.40000	-80.40000	80.40000	32.98672	33.91825
41	0.00035	0.41000	-80.40000	80.40000	32.98672	33.92108
42	0.00036	0.42000	-80.40000	80.40000	32.98672	33.92423
43	0.00037	0.43000	-80.40000	80.40000	32.98672	33.92768
44	0.00038	0.44000	-80.40000	80.40000	32.98672	33.93140
45	0.00039	0.45000	-80.40000	80.40000	32.98672	33.93537
46	0.00039	0.46000	-80.40000	80.40000	32.98672	33.93956
47	0.00040	0.47000	-80.40000	80.40000	32.98672	33.94391
48	0.00041	0.48000	-80.40000	80.40000	32.98672	33.94840
49	0.00042	0.49000	-80.40000	80.40000	32.98672	33.95299
50	0.00043	0.50000	-80.40000	80.40000	32.98672	33.95762

Figure 34. Continued

95TM1

TO CONTINUE THIS CASE READ THE FOLLOWING   VARIABLES IN NAMELIST CONTIN

NT=   51
U(1)= 0.5029428E-03   U(2)= -0.2942818E-05   U(3)= 0.5629093E-04
U(4)= -0.7214560E-03   U(5)= 0.1385060E-03
UDOT(1)= 0.0000000E+00   UDOT(2)= 0.0000000E+00
UDOT(3)= -6.725401   UDOT(4)= 0.1856257E-01
UDOT(5)= -6.786918
UDOTT(1)= 0.0000000E+00   UDOTT(2)= 0.0000000E+00
UDOTT(3)= 6166.955   UDOTT(4)= 81600.15
UDOTT(5)= -11513.51
FRICX= 80.40000   FRICY= -80.40000
FRICZ= 32.98672   FRICA=   33.95762
FRICB= 33.95762

Figure 34. Continued

```
SAMPLE3M
DYSEAL SAMPLE3M INPUT
*
*GEOMETRY
NUNIT        2
PISTON
TOTAL
ZSCO      0.0181
ROS       0.0401
RIS       0.0315
RSCI      0.0310
RSCO      0.0356
RSP       0.0397
NELM      3
ZSPO      0.0064
THETO     0.0
DTHET     .5236
RIEL(20)  .0260   .0260  .0260
ROEL(20)  .0401   .0452  .0310
ELEML(20) .0023   .0041  .0156
DENS(20)  6926.  6926.  6926.
ZL(20)    0.0  .0023  .0064
APR       3.458E-04
WPR       .000635
*SPRING AND DAMPING
SPPRE     0.6672
NOSP      12
SKZZ      73724724.
SKZA      0.0
SKZB      0.0
SKBZ      0.0
SKBB      40812.
*SKBA     0.0
*SKAZ     0.0
*SKAB     0.0
SKAA      40812.
DZZ       0.0
DZB       0.0
DZA       0.0
DBZ       0.0
DBB       0.0
DBA       0.0
DAZ       0.0
DAB       0.0
DAA       0.0
SPRST     884.
HO        2.972E-05
FFL       10564.
*OPERATING CONDITIONS
OMEGA     7330.
POD       5170810.
PID       0.0
COFSC     .2
VISC      1.1720E-04
DT        8.5718876E-06
NTS       50
NT        1
*INITIAL CONDITIONS
XO        1.27E-05
YO        1.27E-05
ZO        1.27E-05
AO        0.0005
BO        0.0005
OMEGAX    7330.
OMEGAY    7330.
OMEGAZ    7330.
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TINIT     0.0
OMEGAB    7330.
OMEGAA    7330.
END
```

95TM1

Figure 35. Sample Problem 3M (Metric) Input

ECHO OF INPUT

DYSEAL SAMPLE3M INPUT

*
*GEOMETRY

NUNIT   2.000   = 1 FOR ENG.(DEFAULT), 2 FOR METRIC
PISTON   T   = TRUE IF SECONDARY PISTON RING
TOTAL   T   = TRUE FOR FORMATTED PRINTOUT
ZSCO   0.1810E-01 =AXIAL DISTANCE TO SECONDARY SEAL
ROS   0.4010E-01 =OUTSIDE RADIUS OF SEAL INTERFACE
RIS   0.3150E-01 =INSIDE RADIUS OF SEAL INTERFACE
RSCI   0.3100E-01 =PISTON RING INSIDE RADIUS
RSCO   0.3560E-01 =PISTON RING OUTSIDE RADIUS
RSP   0.3970E-01 =MEAN SPRING RADIUS
NELM   3.000   =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO   0.6400E-02 =AXIAL DISTANCE TO CLOSING SPRINGS
THETO   0.0000E+00 =ANGLE TO FIRST CLOSING SPRING
DTHET   0.5236   =ANGLE BETWEEN SPRINGS,
RIEL(20) =INSIDE RADIUS OF ELEMENT
   0.2600E-01 0.2600E-01 0.2600E-01 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00
ROEL(20) =OUTSIDE RADIUS OF ELEMENT
   0.4010E-01 0.4520E-01 0.3100E-01 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00
ELEML(20) =ELEMENT LENGTH
   0.2300E-02 0.4100E-02 0.1560E-01 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00
DENS(20) =ELEMENT DENSITY
   6926.   6926.   6926.   0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00
ZL(20)   =AXIAL DIST. FROM INTERFACE TO ELEM.
   0.0000E+00 0.2300E-02 0.6400E-02 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00

Figure 36. Sample Problem 3M (Metric) Output

95TM1

1

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APR      0.3458E-03   =UNBALANCED PISTON RING FACE AREA
WPR      0.6350E-03   =CIRCUMFERENTIAL PISTON RING WIDTH
*SPRING AND DAMPING
SPPRE  = 0.6672        SINGLE SPRING PRELOAD
NOSP   = 12.00         NUMBER OF SPRINGS
SKZZ   = 0.7372E+08    FLUID-FILM STIFFNESS, KZZ
SKZA   = 0.0000E+00    FLUID-FILM STIFFNESS, KZA
SKZB   = 0.0000E+00    FLUID-FILM STIFFNESS, KZB
SKBZ   = 0.0000E+00    FLUID-FILM STIFFNESS, KBZ
SKBB   = 0.4081E+05    FLUID-FILM STIFFNESS, KBB
*SKBA    0.0
*SKAZ    0.0
*SKAB    0.0
SKAA   = 0.4081E+05    FLUID-FILM STIFFNESS, KAA
DZZ    = 0.0000E+00    FLUID-FILM DAMPING
DZB    = 0.0000E+00    FLUID-FILM DAMPING
DZA    = 0.0000E+00    FLUID-FILM DAMPING
DBZ    = 0.0000E+00    FLUID-FILM DAMPING
DBB    = 0.0000E+00    FLUID-FILM DAMPING
DBA    = 0.0000E+00    FLUID-FILM DAMPING
DAZ    = 0.0000E+00    FLUID-FILM DAMPING
DAB    = 0.0000E+00    FLUID-FILM DAMPING
DAA    = 0.0000E+00    FLUID-FILM DAMPING
SPRST  = 884.0         CLOSING SPRING STIFFNESS
HO     = 0.2972E-04    EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL    = 0.1056E+05    EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA  = 7330.         SHAFT ROTATIONAL SPEED
POO    = 0.5171E+07    OD PRESSURE
PID    = 0.0000E+00    ID PRESSURE
COFSC  = 0.2000        COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC   = 0.1172E-03    FLUID FILM VISCOSITY
DT     = 0.8572E-05    VALUE OF TIME STEP INCREMENT
NTS    = 50.00         NUMBER OF TIME STEPS
NT     = 1.000         INITIAL TIME STEP NUMBER
*INITIAL CONDITIONS
XO     = 0.1270E-04    SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO     = 0.1270E-04    SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO     = 0.1270E-04    SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
AO     = 0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
BO     = 0.5000E-03    SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
OMEGAX = 7330.         SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
OMEGAY = 7330.         SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
OMEGAZ = 7330.         SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
TINIT  = 0.0000E+00    INITIAL TIME, SEC
```

Figure 36. Continued

OMEGAB = 7330.   SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
OMEGAA = 7330.   SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S
....

TOTAL MASS,KG. = 0.2653358

CG DISTANCE, M. = 0.7378705E-02

POLAR MOMENT OF INERTIA,KG-M**2 = 0.2982462E-03

TRANSVERSE MOMENT OF INERTIA,KG-M**2 = 0.1587059E-03

....

ACL=CLOSING AREA,M**2= 0.2032642E-02

FHCL=HYDRAULIC CLOSING FORCE,N= 10510.40

AIF=INTERFACE AREA,M**2, = 0.1934467E-02

FIFPRE=INTERFACE PRELOAD,N= 10518.41

SCFRIC=SECONDARY SEAL PRELOAD FRICTION,N= 146.8900

HO=INITIAL FILM THICKNESS OR INTERFERENCE,M= 0.2972000E-04

....

Figure 36. Continued

SEAL MOTIONS, AND CLEARANCE, MICRONS AND MICRO-RADIANS

STEP	TIME	REVS	X-DISPL.	Y-DISPL.	Z-DISPL.	XX-DISPL.	YY-DISPL.	FILM-THK.
1	0.00001	0.01000	12.70000	0.00000	0.00000	500.00000	0.00000	28.92256
2	0.00002	0.02000	12.70000	0.00000	0.00000	500.00000	0.00000	28.12827
3	0.00003	0.03000	12.70000	0.00000	0.00197	500.00000	0.00000	27.34222
4	0.00003	0.04000	12.72476	0.00000	0.01375	500.00000	0.00000	26.57539
5	0.00004	0.05000	12.72476	-0.02476	0.04887	499.44278	0.28474	25.84435
6	0.00005	0.06000	12.77427	-0.07427	0.12217	497.17436	1.55731	25.16698
7	0.00006	0.07000	12.77427	-0.07427	0.24738	492.52149	4.49194	24.55998
8	0.00007	0.08000	12.77427	-0.07427	0.43682	486.22070	9.57504	24.03855
9	0.00008	0.09000	12.77427	-0.07427	0.70108	479.88927	17.23683	23.61608
10	0.00009	0.10000	12.77427	-0.07427	1.04871	474.22924	27.84118	23.30384
11	0.00009	0.11000	12.77427	-0.07427	1.48604	469.01533	41.67675	23.11076
12	0.00010	0.12000	12.77427	-0.07427	2.01699	463.98384	58.94965	23.04324
13	0.00011	0.13000	12.77427	-0.07427	2.64290	458.83910	79.77771	23.10500
14	0.00012	0.14000	12.77427	-0.07427	3.36252	453.26050	104.18652	23.29700
15	0.00013	0.15000	12.77427	-0.07427	4.17192	446.91020	132.10733	23.61741
16	0.00014	0.16000	12.77427	-0.07427	5.06460	439.44124	163.37676	24.06163
17	0.00015	0.17000	12.77427	-0.07427	6.03151	430.50589	197.73846	24.62241
18	0.00015	0.18000	12.77427	-0.07427	7.06125	419.76413	234.84665	25.28994
19	0.00016	0.19000	12.77427	-0.07427	8.14025	406.89204	274.27139	26.05209
20	0.00017	0.20000	12.77427	-0.07427	9.25303	391.58997	315.50564	26.89461
21	0.00018	0.21000	12.77427	-0.07427	10.38245	373.59034	357.97387	27.80145
22	0.00019	0.22000	12.77427	-0.07427	11.51010	352.66483	401.04206	28.75506
23	0.00020	0.23000	12.77427	-0.07427	12.61660	328.63096	444.02903	29.73674
24	0.00021	0.24000	12.77427	-0.07427	13.68200	301.35774	486.21870	30.72706
25	0.00021	0.25000	12.77427	-0.07427	14.68617	270.77048	526.87319	31.70617
26	0.00022	0.26000	12.77427	-0.07427	15.60924	236.85453	565.24651	32.65430
27	0.00023	0.27000	12.77427	-0.07427	16.43193	199.65783	600.59848	33.55207
28	0.00024	0.28000	12.77427	-0.07427	17.13602	159.29239	632.20875	34.38097
29	0.00025	0.29000	12.77427	-0.07427	17.70465	115.93447	659.39055	35.12365
30	0.00026	0.30000	12.77427	-0.07427	18.12276	69.82361	681.50397	35.76435
31	0.00027	0.31000	12.77427	-0.07427	18.37734	21.26036	697.96851	36.28917
32	0.00027	0.32000	12.77427	-0.07427	18.45771	-29.39712	708.27463	36.68641
33	0.00028	0.33000	12.77427	-0.07427	18.37606	-81.73761	711.99416	36.96697
34	0.00029	0.34000	12.77427	-0.07427	18.16717	-135.30240	708.78923	37.16421
35	0.00030	0.35000	12.77427	-0.07427	17.84728	-189.59189	699.30158	37.29276
36	0.00031	0.36000	12.77427	-0.07427	17.41377	-244.07293	685.14171	37.34825
37	0.00032	0.37000	12.77427	-0.07427	16.85554	-298.18699	667.09618	37.32764
38	0.00033	0.38000	12.77427	-0.07427	16.20302	-351.35877	645.11423	37.22927

Figure 36. Continued

95TM1

39	0.00033	0.39000	12.77427	-0.07427	15.42822	-403.00531	619.19216	37.05294
40	0.00034	0.40000	12.77427	-0.07427	14.54473	-452.54530	589.37498	36.79986
41	0.00035	0.41000	12.77427	-0.07427	13.55772	-499.40845	555.75741	36.47271
42	0.00036	0.42000	12.77427	-0.07427	12.47383	-543.04483	518.48385	36.07556
43	0.00037	0.43000	12.77427	-0.07427	11.30116	-582.93387	477.74761	35.61376
44	0.00038	0.44000	12.77427	-0.07427	10.04910	-618.59300	433.78932	35.09392
45	0.00039	0.45000	12.77427	-0.07427	8.72824	-649.58566	386.89442	34.52372
46	0.00039	0.46000	12.77427	-0.07427	7.35017	-675.52856	337.38997	33.91180
47	0.00040	0.47000	12.77427	-0.07427	5.92733	-696.09814	285.64067	33.26759
48	0.00041	0.48000	12.77427	-0.07427	4.47285	-711.03599	232.04423	32.60111
49	0.00042	0.49000	12.77427	-0.07427	3.00026	-720.15323	177.02615	31.92282
50	0.00043	0.50000	12.77427	-0.07427	1.52338	-723.33364	121.03407	31.24338

Figure 36. Continued

SHAFT MOTIONS, MICRONS AND MICRO-RADIANS

STEP	TIME	REVS	X-DISPL.	Y-DISPL.	Z-DISPL	XX-DISPL.	YY-DISPL.	HMIN
1	0.00001	0.01000	12.67494	0.79744	0.79744	499.01336	31.39526	27.66361
2	0.00002	0.02000	12.59986	1.59173	1.59173	496.05735	62.66661	25.61112
3	0.00003	0.03000	12.47505	2.37974	2.37974	491.14363	93.69065	23.56857
4	0.00003	0.04000	12.30101	3.15836	3.15836	484.29158	124.34494	21.55323
5	0.00004	0.05000	12.07842	3.92452	3.92452	475.52826	154.50849	19.58741
6	0.00005	0.06000	11.80816	4.67518	4.67518	464.88825	184.06227	17.73490
7	0.00006	0.07000	11.49130	5.40740	5.40740	452.41353	212.88964	16.05091
8	0.00007	0.08000	11.12909	6.11827	6.11827	438.15334	240.87683	14.56956
9	0.00008	0.09000	10.72296	6.80500	6.80500	422.16397	267.91339	13.30736
10	0.00009	0.10000	10.27452	7.46487	7.46487	404.50850	293.89262	12.27509
11	0.00009	0.11000	9.78552	8.09528	8.09528	385.25663	318.71199	11.51088
12	0.00010	0.12000	9.25790	8.69375	8.69375	364.48432	342.27354	11.00248
13	0.00011	0.13000	8.69375	9.25790	9.25790	342.27356	364.48430	10.77808
14	0.00012	0.14000	8.09528	9.78552	9.78552	318.71201	385.25661	10.80189
15	0.00013	0.15000	7.46487	10.27452	10.27452	293.89264	404.50849	11.08956
16	0.00014	0.16000	6.80500	10.72296	10.72296	267.91341	422.16395	11.61578
17	0.00015	0.17000	6.11827	11.12909	11.12909	240.87685	438.15333	12.34942
18	0.00015	0.18000	5.40740	11.49130	11.49130	212.88966	452.41352	13.25492
19	0.00016	0.19000	4.67518	11.80816	11.80816	184.06229	464.88824	14.29382
20	0.00017	0.20000	3.92452	12.07842	12.07842	154.50852	475.52825	15.42637
21	0.00018	0.21000	3.15836	12.30101	12.30101	124.34496	484.29158	16.60243
22	0.00019	0.22000	2.37974	12.47505	12.47505	93.69068	491.14362	17.76073
23	0.00020	0.23000	1.59173	12.59986	12.59986	62.66664	496.05735	18.87131
24	0.00021	0.24000	0.79744	12.67494	12.67494	31.39528	499.01336	19.89804
25	0.00021	0.25000	0.00000	12.70000	12.70000	0.00002	500.00000	20.79567
26	0.00022	0.26000	-0.79744	12.67494	12.67494	-31.39523	499.01337	21.57660
27	0.00023	0.27000	-1.59173	12.59986	12.59986	-62.66659	496.05735	22.23347
28	0.00024	0.28000	-2.37974	12.47505	12.47505	-93.69063	491.14363	22.76711
29	0.00025	0.29000	-3.15836	12.30101	12.30101	-124.34492	484.29159	23.20560
30	0.00026	0.30000	-3.92452	12.07842	12.07842	-154.50847	475.52827	23.56298
31	0.00027	0.31000	-4.67518	11.80816	11.80816	-184.06225	464.88825	23.83697
32	0.00027	0.32000	-5.40740	11.49130	11.49130	-212.88962	452.41354	24.06148
33	0.00028	0.33000	-6.11827	11.12910	11.12910	-240.87681	438.15336	24.26639
34	0.00029	0.34000	-6.80500	10.72297	10.72297	-267.91337	422.16398	24.50005
35	0.00030	0.35000	-7.46487	10.27452	10.27452	-293.89260	404.50852	24.75398
36	0.00031	0.36000	-8.09528	9.78552	9.78552	-318.71197	385.25664	24.95796
37	0.00032	0.37000	-8.69375	9.25790	9.25790	-342.27353	364.48434	25.07027
38	0.00033	0.38000	-9.25790	8.69375	8.69375	-364.48429	342.27358	25.08536
39	0.00033	0.39000	-9.78552	8.09529	8.09529	-385.25660	318.71202	24.98750
40	0.00034	0.40000	-10.27452	7.46487	7.46487	-404.50847	293.89266	24.79653
41	0.00035	0.41000	-10.72296	6.80500	6.80500	-422.16394	267.91343	24.52178

Figure 36. Continued

95TM1

42	0.00036	0.42000	-11.12909	6.11827	6.11827	-438.15332	240.87687	24.17627
43	0.00037	0.43000	-11.49130	5.40740	5.40740	-452.41351	212.88968	23.77612
44	0.00038	0.44000	-11.80816	4.67518	4.67518	-464.88823	184.06232	23.33972
45	0.00039	0.45000	-12.07842	3.92452	3.92452	-475.52824	154.50854	22.88692
46	0.00039	0.46000	-12.30101	3.15836	3.15836	-484.29157	124.34499	22.43812
47	0.00040	0.47000	-12.47505	2.37974	2.37974	-491.14362	93.69070	22.01337
48	0.00041	0.48000	-12.59986	1.59173	1.59173	-496.05734	62.66666	21.63148
49	0.00042	0.49000	-12.67494	0.79744	0.79744	-499.01336	31.39531	21.30925
50	0.00043	0.50000	-12.70000	0.00000	0.00000	-500.00000	0.00005	21.06080

Figure 36. Continued

FRICTION AND INTERFACE FORCES

STEP	TIME	REVS.	X-FRICT	Y-FRICT	Z-FRICT	XX-FRICT	YY-FRICT
1	0.00001	0.01000	357.61322	-357.61322	-146.88998	-3.83408	-3.83408
2	0.00002	0.02000	357.61322	-357.61322	-146.88998	-3.83408	-3.83408
3	0.00003	0.03000	357.61322	-357.61322	-146.88998	-3.83408	-3.83408
4	0.00003	0.04000	357.61322	-357.61322	-146.88998	-3.83408	-3.83408
5	0.00004	0.05000	357.61322	-357.61322	-146.88998	-3.83407	-3.83407
6	0.00005	0.06000	-357.61322	357.61322	-146.88998	-3.83406	-3.83406
7	0.00006	0.07000	-357.61322	357.61322	-146.88998	-3.83403	-3.83403
8	0.00007	0.08000	-357.61322	-357.61322	-146.88998	3.83399	-3.83399
9	0.00008	0.09000	-357.61322	-357.61322	-146.88998	3.83392	-3.83392
10	0.00009	0.10000	-357.61322	-357.61322	-146.88998	3.83383	-3.83383
11	0.00009	0.11000	-357.61322	-357.61322	-146.88998	3.83370	-3.83370
12	0.00010	0.12000	-357.61322	-357.61322	-146.88998	3.83355	-3.83355
13	0.00011	0.13000	-357.61322	-357.61322	-146.88998	3.83336	-3.83336
14	0.00012	0.14000	-357.61322	-357.61322	-146.88998	3.83313	-3.83313
15	0.00013	0.15000	-357.61322	-357.61322	-146.88998	3.83287	-3.83287
16	0.00014	0.16000	-357.61322	-357.61322	-146.88998	3.83258	-3.83258
17	0.00015	0.17000	-357.61322	-357.61322	-146.88998	3.83227	-3.83227
18	0.00015	0.18000	-357.61322	-357.61322	-146.88998	3.83192	-3.83192
19	0.00016	0.19000	-357.61322	-357.61322	-146.88998	3.83155	-3.83155
20	0.00017	0.20000	-357.61322	-357.61322	-146.88998	3.83117	-3.83117
21	0.00018	0.21000	-357.61322	-357.61322	-146.88998	3.83077	-3.83077
22	0.00019	0.22000	-357.61322	-357.61322	-146.88998	3.83036	-3.83036
23	0.00020	0.23000	-357.61322	-357.61322	-146.88998	3.82996	-3.82996
24	0.00021	0.24000	-357.61322	-357.61322	-146.88998	3.82956	-3.82956
25	0.00021	0.25000	-357.61322	-357.61322	-146.88998	3.82918	-3.82918
26	0.00022	0.26000	-357.61322	-357.61322	-146.88998	3.82882	-3.82882
27	0.00023	0.27000	-357.61322	-357.61322	-146.88998	3.82849	-3.82849
28	0.00024	0.28000	-357.61322	-357.61322	-146.88998	3.82820	-3.82820
29	0.00025	0.29000	-357.61322	-357.61322	-146.88998	3.82795	-3.82795
30	0.00026	0.30000	-357.61322	-357.61322	-146.88998	3.82775	-3.82775
31	0.00027	0.31000	-357.61322	-357.61322	-146.88998	3.82760	-3.82760

Figure 36. Continued

95TM1

32	0.00027	0.32000	-357.61322	-357.61322	-146.88998	3.82750	-3.82750
33	0.00028	0.33000	-357.61322	-357.61322	146.88998	3.82748	-3.82748
34	0.00029	0.34000	-357.61322	-357.61322	146.88998	3.82751	-3.82751
35	0.00030	0.35000	357.61322	-357.61322	146.88998	3.82758	3.82758
36	0.00031	0.36000	357.61322	-357.61322	146.88998	3.82769	3.82769
37	0.00032	0.37000	357.61322	-357.61322	146.88998	3.82785	3.82785
38	0.00033	0.38000	357.61322	-357.61322	146.88998	3.82805	3.82805
39	0.00033	0.39000	357.61322	-357.61322	146.88998	3.82828	3.82828
40	0.00034	0.40000	357.61322	-357.61322	146.88998	3.82856	3.82856
41	0.00035	0.41000	357.61322	-357.61322	146.88998	3.82888	3.82888
42	0.00036	0.42000	357.61322	-357.61322	146.88998	3.82923	3.82923
43	0.00037	0.43000	357.61322	-357.61322	146.88998	3.82962	3.82962
44	0.00038	0.44000	357.61322	-357.61322	146.88998	3.83004	3.83004
45	0.00039	0.45000	357.61322	-357.61322	146.88998	3.83048	3.83048
46	0.00039	0.46000	357.61322	-357.61322	146.88998	3.83096	3.83096
47	0.00040	0.47000	357.61322	-357.61322	146.88998	3.83145	3.83145
48	0.00041	0.48000	357.61322	-357.61322	146.88998	3.83196	3.83196
49	0.00042	0.49000	357.61322	-357.61322	146.88998	3.83248	3.83248
50	0.00043	0.50000	357.61322	-357.61322	146.88998	3.83300	3.83300

Figure 36. Continued

95TM1

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TO CONTINUE THIS CASE READ THE FOLLOWING     VARIABLES IN NAMELIST CONTIN

NT=     51
U(1)=  0.1277427E-04    U(2)= -0.7427270E-07    U(3)=  0.1523380E-05
U(4)= -0.7233336E-03    U(5)=  0.1210341E-03
UDOT(1)=  0.0000000E+00    UDOT(2)=  0.0000000E+00
UDOT(3)= -0.1721403    UDOT(4)= -0.2242281E-01
UDOT(5)= -6.575550
UDOTT(1)=  0.0000000E+00    UDOTT(2)=  0.0000000E+00
UDOTT(3)=   130.2618    UDOTT(4)=   81621.03
UDOTT(5)=  -6979.241
FRICX=  357.6132    FRICY=  -357.6132
FRICZ=  146.8900    FRICA=  3.833004
FRICB=  3.833004
```

Figure 36. Continued
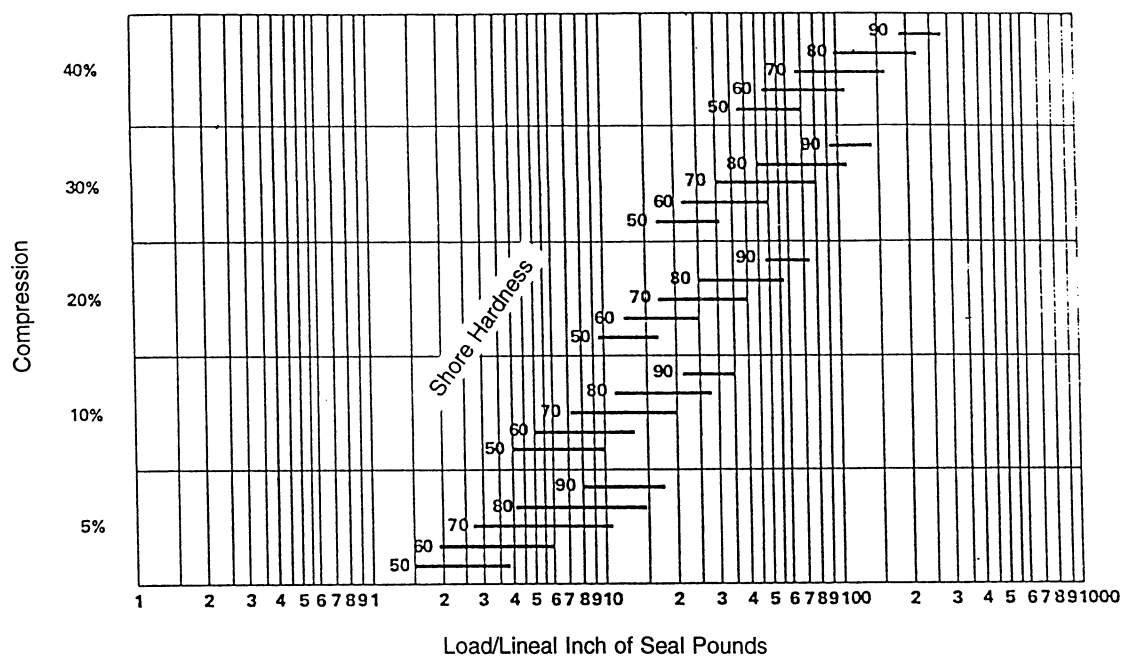
a) 0.210-in. Cross Section
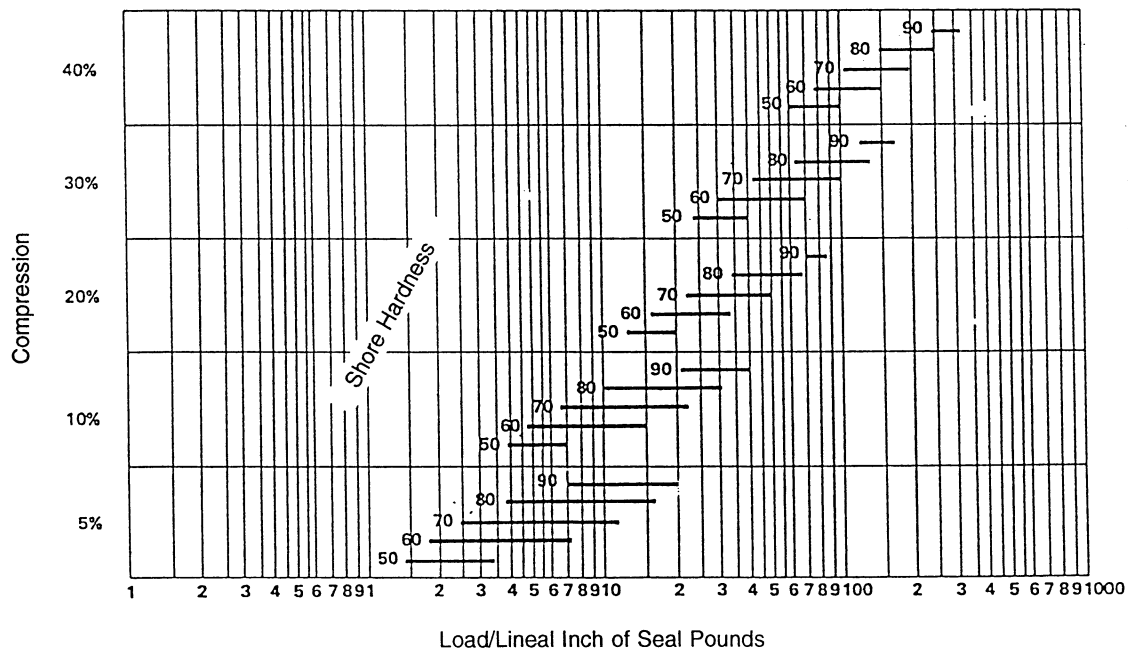
b) 0.275-in. Cross Section

95TM1

Figure 37. Typical O-Ring Data for Computing SKEL and SCPREL

```
ORING
DYSEAL O-RING SAMPLE PROBLEM
*
HELP
*GEOMETRY
ORING
ZSCO       0.712
ROS        1.58
RIS        1.24
RSC        1.31
RSP        1.5625
NELM       3
ZSPO       0.2525
THETO      0.0
DTHET      .5236
RIEL(20)   1.025   1.025   1.025
ROEL(20)   1.580   1.780   1.220
ELEML(20)  .0925   .1600   .6125
DENS(20)   .250    .250    .250
ZL(20)     0.0     .0925   .2525   .2525
*SPRING AND DAMPING
SPPRE      .150
NOSP       12
SKZZ       421000.
SK2A       0.0
SK2B       0.0
SKBZ       0.0
SKBB       361239.
*SKBA      0.0
*SKAZ      0.0
*SKAB      0.0
SKAA       361239.
DZZ        0.0
DZB        0.0
DZA        0.0
DBZ        0.0
DBB        0.0
DBA        0.0
DAZ        0.0
DAB        0.0
DAA        0.0
SPRST      5.050
SKEL       10.
SCPREL     10.
DEL        0.243
HO         .00117
FFL        2375.0
*OPERATING CONDITIONS
OMEGA      7330.
POD        750.
PID        0.0
COFSC      .2
VISC       1.7E-08
DT         8.571876E-06
NTS        1000
NT         1
*INITIAL CONDITIONS
XO         .0005
YO         .0005
ZO         .0005
AO         .0005
BO         .0005
OMEGAX     7330.
OMEGAY     7330.
OMEGAZ     7330.
TINIT      0.0
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OMEGAB     7330.
OMEGAA     7330.
END
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95TM1

Figure 38. O-Ring Sample Problem Input

95TM1

ECHO OF INPUT

DYSEAL O-RING SAMPLE PROBLEM

*

```
DYSEAL INPUT INSTRUCTIONS
ZSCO      =AXIAL DISTANCE TO SECONDARY SEAL
ROS       =OUTSIDE RADIUS OF SEAL INTERFACE
RIS       =INSIDE RADIUS OF SEAL INTERFACE
RSCI      =PISTON RING INSIDE RADIUS
RSCO      =PISTON RING OUTSIDE RADIUS
RSC       =O-RING SECONDARY SEAL RADIUS
RSP       =MEAN SPRING RADIUS
ZSPO      =AXIAL DISTANCE TO CLOSING SPRINGS
THETO     =ANGLE TO FIRST CLOSING SPRING
DTHET     =ANGLE BETWEEN SPRINGS,
NELM      =NUMBER OF GEOMETRICAL ELEMENTS
RIEL(20)  =INSIDE RADIUS OF ELEMENT
ROEL(20)  =OUTSIDE RADIUS OF ELEMENT
ELEML(20) =ELEMENT LENGTH
DENS(20)  =ELEMENT DENSITY
EMOD      =ELASTIC MODULUS OF RING SEAL
APR       =UNBALANCED PISTON RING FACE AREA
WPR       =CIRCUMFERENTIAL PISTON RING FACE WIDTH
ZL(20)    =AXIAL DIST. FROM INTERFACE TO ELEM.
INSIDE    =1, ID PISTON RING
PISTON    = TRUE IF SECONDARY PISTON RING
ORING     = TRUE IF SECONDARY O-RING
RING      = TRUE FOR A RING SEAL
TOTAL     = TRUE FOR FORMATTED PRINTOUT
NUNIT     = 1 FOR ENG.(DEFAULT), 2 FOR METRIC

SPPRE     =SINGLE SPRING PRELOAD
NOSP      =NUMBER OF SPRINGS
SKXX      =FLUID-FILM STIFFNESS, KXX
SKXY      =FLUID-FILM STIFFNESS, KXY
SKYX      =FLUID-FILM STIFFNESS, KYX
SKYY      =FLUID-FILM STIFFNESS, KYY
SKZZ      =FLUID-FILM STIFFNESS, KZZ
SKZB      =FLUID-FILM STIFFNESS, KZB
SKZA      =FLUID-FILM STIFFNESS, KZA
SKBZ      =FLUID-FILM STIFFNESS, KBZ
SKBB      =FLUID-FILM STIFFNESS, KBB
SKBA      =FLUID-FILM STIFFNESS, KBA
SKAZ      =FLUID-FILM STIFFNESS, KAZ
SKAB      =FLUID-FILM STIFFNESS, KAB
SKAA      =FLUID-FILM STIFFNESS, KAA

DYY       =FLUID-FILM DAMPING
DYX       =FLUID-FILM DAMPING
DXY       =FLUID-FILM DAMPING
DXX       =FLUID-FILM DAMPING
DZZ       =FLUID-FILM DAMPING
DZB       =FLUID-FILM DAMPING
DZA       =FLUID-FILM DAMPING
DBZ       =FLUID-FILM DAMPING
DBB       =FLUID-FILM DAMPING
DBA       =FLUID-FILM DAMPING
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```
DAZ       =FLUID-FILM DAMPING
DAB       =FLUID-FILM DAMPING
DAA       =FLUID-FILM DAMPING
SPRST     =CLOSING SPRING STIFFNESS
FFL       = EQUILIBRIUM FLUID-FILM FORCE
HO        = EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
CO        = RING SEAL CLEARANCE
SKEL      = O-RING STIFFNESS PER UNIT LENGTH
DEL       = O-RING DAMPING PER UNIT LENGTH
SCPREL    = O-RING AND PISTON RING PRELOAD PER UNIT LENGTH

OMEGA     =SHAFT ROTATIONAL SPEED
POD       =OD PRESSURE
PID       =ID PRESSURE
COFSC     =COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC      =FLUID FILM VISCOSITY
DT        =VALUE OF TIME STEP INCREMENT
NTS       =NUMBER OF TIME STEPS
NT        =INITIAL TIME STEP NUMBER

XO        = SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO        = SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO        = SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
BO        = SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,RAD.
AO        = SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,RAD.
OMEGAX    = SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS, RAD/S
OMEGAY    = SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS, RAD/S
OMEGAZ    = SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS, RAD/S
OMEGAB    = SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS, RAD/S
OMEGAA    = SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS, RAD/S
TINIT     = INITIAL TIME, SEC
CONT      = TRUE IF THE RUN IS A CONTINUATION
SPPRE     =SINGLE SPRING PRELOAD

U(5)      =SEAL DISPLACEMENTS
UDOT(5 )  =SEAL VELOCITIES
UDOTT(5)  =SEAL ACCELERATIONS
FRICX     =FRICTION FORCE IN X DIRECTION
FRICY     =FRICTION FORCE IN Y DIRECTION
FRICZ     =FRICTION FORCE IN Z DIRECTION
FRICB     =FRICTION MOMENT ABOUT X-X AXIS
FRICA     =FRICTION MOMENT ABOUT Y-Y AXIS

*GEOMETRY
ORING             T        = TRUE IF SECONDARY O-RING
ZSCO       0.7120          =AXIAL DISTANCE TO SECONDARY SEAL
ROS        1.580           =OUTSIDE RADIUS OF SEAL INTERFACE
RIS        1.240           =INSIDE RADIUS OF SEAL INTERFACE
RSC        1.310           =O-RING SECONDARY SEAL RADIUS
RSP        1.563           =MEAN SPRING RADIUS
NELM       3.000           =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO       0.2525          =AXIAL DISTANCE TO CLOSING SPRINGS
THETO      0.0000E+00      =ANGLE TO FIRST CLOSING SPRING
DTHET      0.5236          =ANGLE BETWEEN SPRINGS,
RIEL(20)                   =INSIDE RADIUS OF ELEMENT
           1.025    1.025    0.0000E+00  0.0000E+00  0.0000E+00
           0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
           0.0000E+00  0.0000E+00  0.0000E+00
ROEL(20)                   =OUTSIDE RADIUS OF ELEMENT
```

Figure 39. O-Ring Sample Problem Output

```
YO      = 0.5000E-03     SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO      = 0.5000E-03     SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
AO      = 0.5000E-03     SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,R
AD.
BO      = 0.5000E-03     SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,R
AD.
OMEGAX  = 7330.          SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS,
RAD/S
OMEGAY  = 7330.          SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS,
RAD/S
OMEGAZ  = 7330.          SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS,
RAD/S
TINIT   = 0.0000E+00     INITIAL TIME, SEC
OMEGAB  = 7330.          SHAFT VIBRATION FREQUENCY ABOUT THE X-X AXIS,
RAD/S
OMEGAA  = 7330.          SHAFT VIBRATION FREQUENCY ABOUT THE Y-Y AXIS,
RAD/S
1
................

        TOTAL MASS,LB.-SEC**2/IN =  0.1505581E-02

        CG DISTANCE,IN. =     0.2895275

        POLAR MOMENT OF INERTIA,LB-SEC**2-IN =   0.2628993E-02

        TRANSVERSE MOMENT OF INERTIA,LB.-SEC**2-IN =   0.1397172E-02

................

ACL=CLOSING AREA,IN**2=      2.451385
FHCL=HYDRAULIC CLOSING FORCE,LBS.=     1838.539
AIF=INTERFACE AREA,IN**2,=     3.012159
FIFPRE=INTERFACE PRELOAD,LBS=    1840.339
SCFRIC=SECONDARY SEAL PRELOAD FRICTION,LBS=     16.46195
HO=INITIAL FILM THICKNESS OR INTERFERENCE,IN.=  0.2400878E-02

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          TO CONTINUE THIS CASE READ THE FOLLOWING     VARIABLES IN NAME
```

```
        1.580       1.780       1.220     0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00
ELEML(20) =ELEMENT LENGTH
    0.9250E-01    0.1600      0.6125    0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00
DENS(20) =ELEMENT DENSITY
        0.2500      0.2500      0.2500  0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00
ZL(20)  =AXIAL DIST. FROM INTERFACE TO ELEM.
    0.0000E+00  0.9250E-01    0.2525    0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    0.0000E+00  0.0000E+00

*SPRING AND DAMPING
SPPRE  =  0.1500          SINGLE SPRING PRELOAD
NOSP   =  12.00           NUMBER OF SPRINGS
SKZZ   =  0.4210E+06      FLUID-FILM STIFFNESS, KZZ
SKZA   =  0.0000E+00      FLUID-FILM STIFFNESS, KZA
SKZB   =  0.0000E+00      FLUID-FILM STIFFNESS, KZB
SKBZ   =  0.0000E+00      FLUID-FILM STIFFNESS, KBZ
SKBB   =  0.3612E+06      FLUID-FILM STIFFNESS, KBB
*SKBA  =  0.0
*SKAZ  =  0.0
*SKAB  =  0.0
SKAA   =  0.3612E+06      FLUID-FILM STIFFNESS, KAA
DZZ    =  0.0000E+00      FLUID-FILM DAMPING
DZB    =  0.0000E+00      FLUID-FILM DAMPING
DZA    =  0.0000E+00      FLUID-FILM DAMPING
DBZ    =  0.0000E+00      FLUID-FILM DAMPING
DBB    =  0.0000E+00      FLUID-FILM DAMPING
DBA    =  0.0000E+00      FLUID-FILM DAMPING
DAZ    =  0.0000E+00      FLUID-FILM DAMPING
DAB    =  0.0000E+00      FLUID-FILM DAMPING
DAA    =  0.0000E+00      FLUID-FILM DAMPING
SPRST  =  5.050           CLOSING SPRING STIFFNESS
SKEL   =  10.00           O-RING STIFFNESS PER UNIT LENGTH
SCPREL =  10.00           O-RING AND PISTON RING PRELOAD PER UNIT LENGTH
DEL    =  0.2430          O-RING DAMPING PER UNIT LENGTH
HO     =  0.1170E-02      EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL    =  2375.           EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA  =  7330.           SHAFT ROTATIONAL SPEED
POD    =  750.0           OD PRESSURE
PID    =  0.0000E+00      ID PRESSURE
COFSC  =  0.2000          COEFFICIENT OF FRICTION,SECONDARY SEAL
VISC   =  0.1700E-07      FLUID FILM VISCOSITY
DT     =  0.8572E-05      VALUE OF TIME STEP INCREMENT
NTS    =  1000.           NUMBER OF TIME STEPS
NT     =  1.000           INITIAL TIME STEP NUMBER
*INITIAL CONDITIONS
XO     =  0.5000E-03      SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
```

Figure 39. Continued

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LIST CONTIN

```
NT=     1001
U(1)= -0.1805574E-07      U(2)=  0.1260268E-07      U(3)= -0.1218275E-03
U(4)=  0.6169198E-03      U(5)= -0.9230165E-05
UDOT(1)=  0.1049967E-04   UDOT(2)=  0.4564146E-05
UDOT(3)=  5.167242        UDOT(4)=  0.4493268
UDOT(5)=  4.518406
UDOTT(1)=  0.4200061E-02  UDOTT(2)=  0.5275602E-01
UDOTT(3)=  27577.41       UDOTT(4)=  -30973.33
UDOTT(5)= -3091.706
FRICX=  0.0000000E+00     FRICY=  0.0000000E+00
FRICZ= -9.776328         FRICA=  -7.654264
FRICB= -0.9934891
```

Figure 39. Continued

95TM1
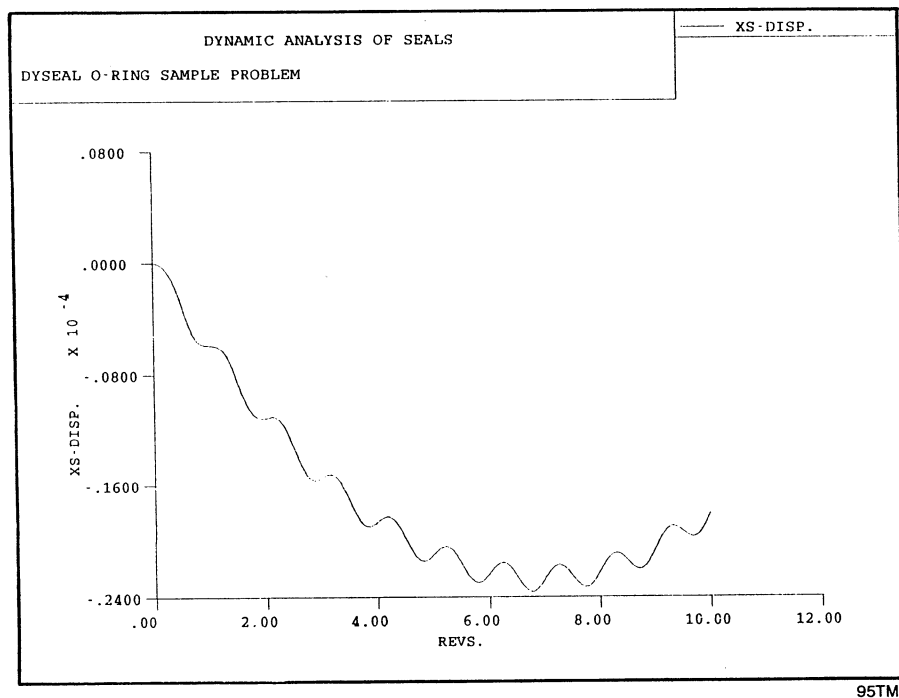
Figure 40. O-Ring Sample Problem x Displacement
versus Shaft Revolutions
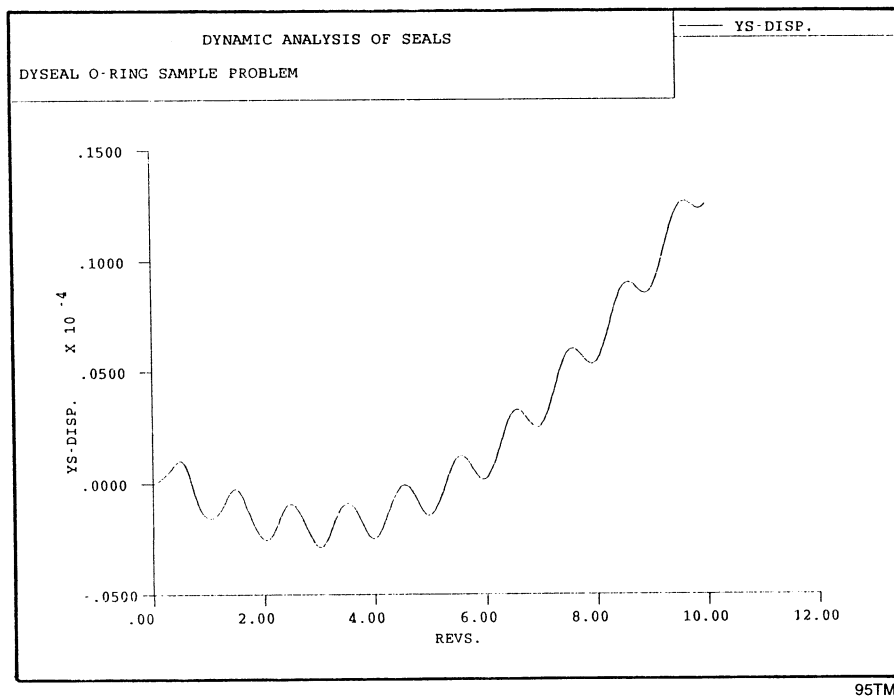
Figure 41. O-Ring Sample Problem y Displacement
versus Shaft Revolutions
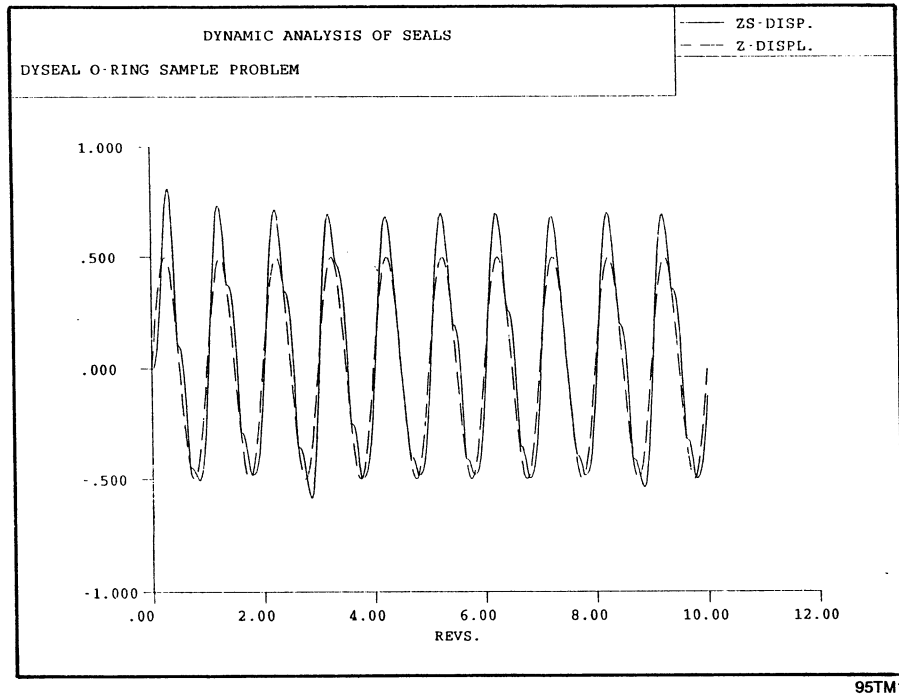
Figure 42. O-Ring Sample Problem Axial Displacement
versus Shaft Revolutions
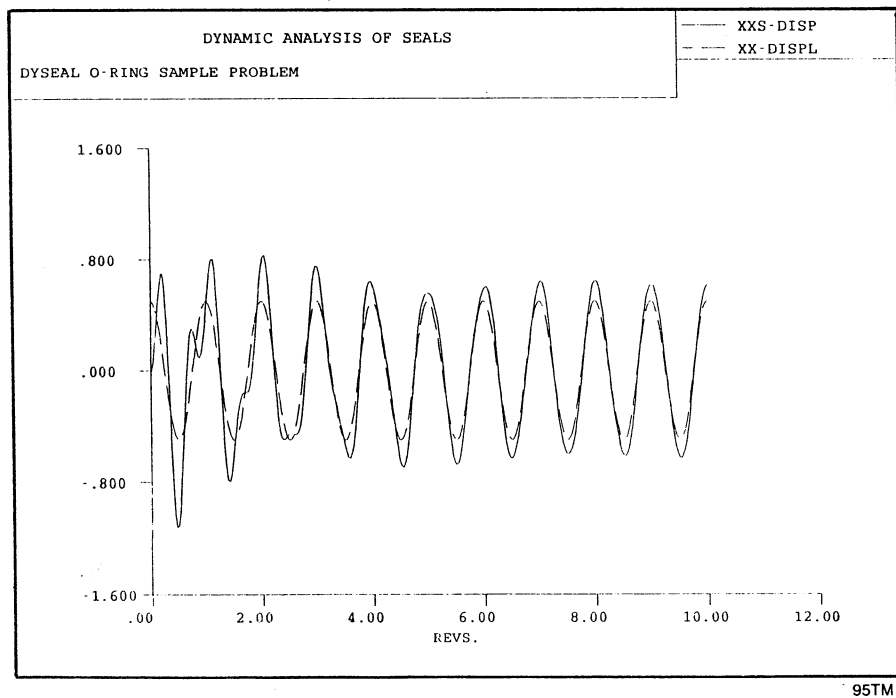
Figure 43. O-Ring Sample Problem Rotation About x Axis
versus Shaft Revolutions
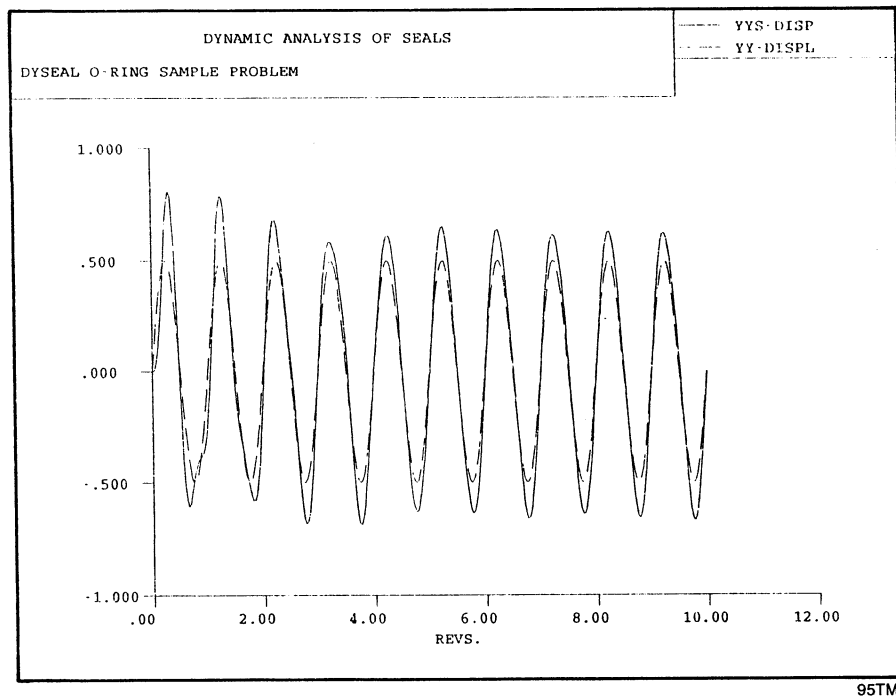
Figure 44. O-Ring Sample Problem Rotation About y Axis
versus Shaft Revolutions
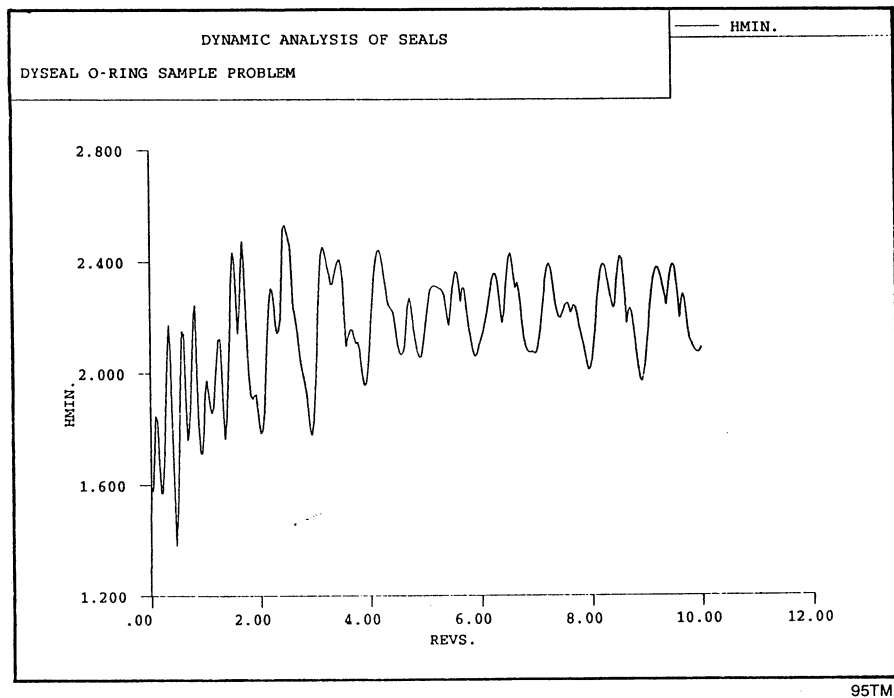
Figure 45. O-Ring Sample Problem Minimum Film Thickness
versus Shaft Revolutions
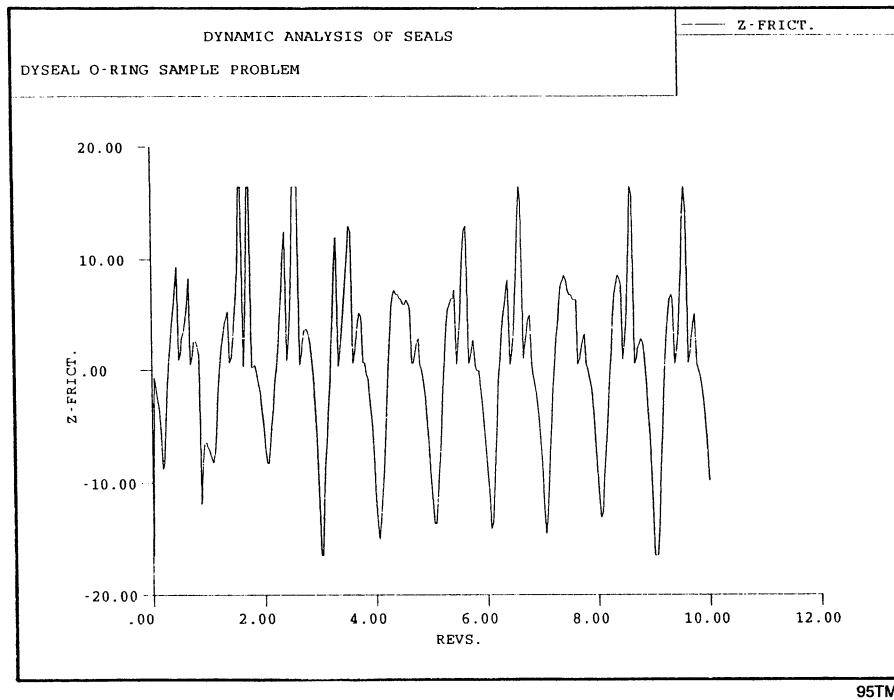
Figure 46. O-Ring Sample Problem Axial Friction
versus Shaft Revolutions
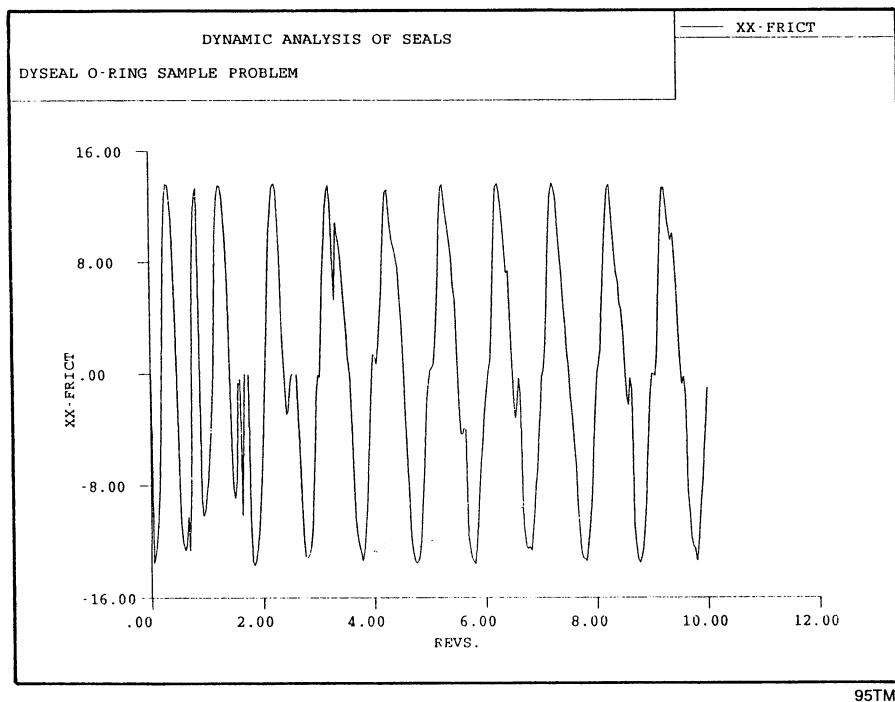
Figure 47. O-Ring Sample Problem Rotational Friction About
x Axis versus Shaft Revolutions
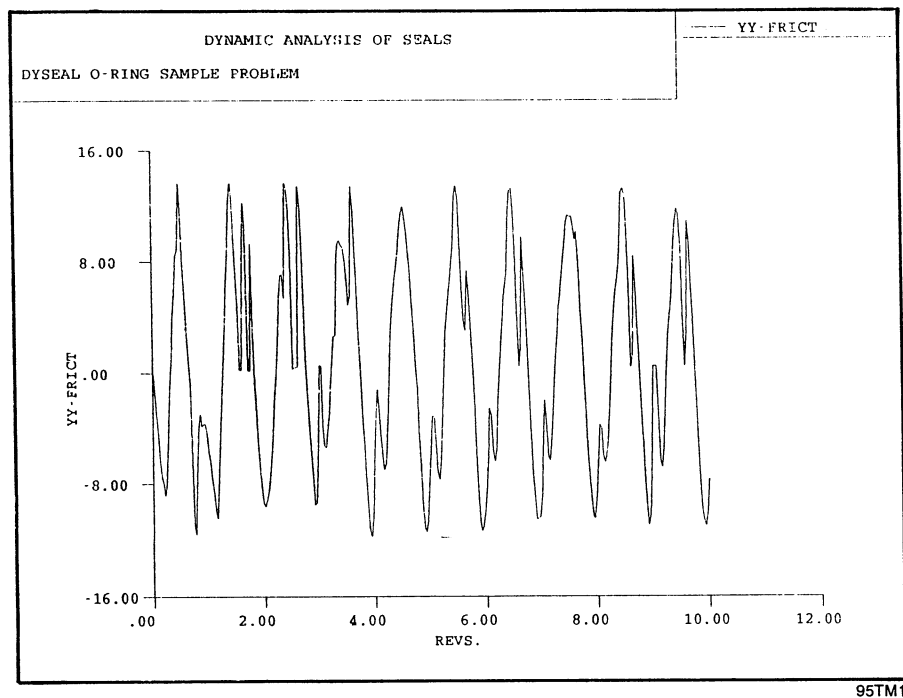
Figure 48. O-Ring Sample Problem Rotational Friction About
y Axis versus Shaft Revolutions

Rotor Transient   Rotor Relative to Seal

Clearance Circle

Seal Ring Transient

814.0			86.1		
WJ	=	200.00	N	=	1780.0
H/V	=	0.00	EMU	=	0.800
WSR	=	2.13	RJ	=	2.090
CR	=	0.0030	L	=	0.904
Viscosity	=	0.8125E-07	Mu-F	=	0.150
F-A	=	20.9000	P-L	=	60.00
P-H	=	72.00	TMAX	=	6.280
P-C	=	-14.70	TH-N	=	36
H	=	0.03140			
NZ	=	6			

WJ	=	Modal mass of rotor shaft (lb_m)
N	=	Rotor shaft speed (rpm)
H/V	=	Horizontal or vertical indicator (1 ≡ horizontal; 0 ≡ vertical)
EMU	=	Rotor shaft modal mass eccentricity relative to seal clearance (DIM)
WSR	=	Seal ring mass (lb_m)
RJ	=	Seal journal radius (in.)
CR	=	Seal radial clearance (in.)
L	=	Seal axial length (in.)
Viscosity	=	Absolute viscosity of sealing fluid (lb-sec/in.^{2})
Mu-F	=	Face friction factor (DIM)
P-H	=	Seal high pressure (lb/in.^{2})
P-L	=	Seal low pressure (lb/in.^{2})
P-C	=	Seal liquid cavitation pressure (lb/in.^{2})
H	=	Time step for transient simulation (rad)
TMAX	=	Maximum time for each segment of response (rad)
NZ	=	Axial grid points for pressure profile
TH-N	=	Pressure profile grid points around circumference of seal

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Figure 49. Pump Seal Transient with Three Cycles of Motion Showing Seal
Tracking Rotor at 0.5 Eccentricity (N = 1780 rpm = 29.7 Hz)

```
KIRK7
CHECK AGAINST G. KIRKS RESULTS, FIG.7
*
*HELP
*GEOMETRY
RING
EMOD          30E06
ROS           2.112
RIS           2.090
RSC           2.090
RSP           2.3
NELM          2
ZSPO          0.904
THETO         0.0
DTHET         0.0
RIEL(20)      2.090  2.090
ROEL(20)      2.112  2.647
ELEML(20)     .125 .779
DENS(20)      0.328 0.328
ZL(20)        0.0 .125
*SPRING AND DAMPING
SPPRE         0.
NOSP          0.
SKXX          4157.
SKXY          -2356.
SKYX
SKYY          25.6
DXX           0.
DXY           0.
DYX           45.4
DYY           0.003
CO            0.0
HO            0.0
FFL
*OPERATING CONDITIONS
OMEGA         186.4
POO           72.
PID           60.
COFSC         0.075
VISC          0.8125E-07
DT            3.3708E-04
NTS           1000
NT            1
*INITIAL CONDITIONS
XO            .0024
YO            .0024
ZO            .000
AO            .00000
BO            .00000
OMEGAX        186.4
OMEGAY        186.4
OMEGAZ        0.
TINIT         0.0
END
```

Figure 50. Kirk's Figure 7 DYSEAL Input (mil)

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ECHO OF INPUT

CHECK AGAINST G. KIRKS RESULTS, FIG.7
*
*HELP
*GEOMETRY
RING   T = TRUE FOR A RING SEAL
EMOD   0.3000E+08   =ELASTIC MODULUS OF RING SEAL
ROS   2.112   =OUTSIDE RADIUS OF SEAL INTERFACE
RIS   2.090   =INSIDE RADIUS OF SEAL INTERFACE
RSC   2.090   =O-RING SECONDARY SEAL RADIUS
RSP   2.300   =MEAN SPRING RADIUS
NELM   2.000   =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO   0.9040   =AXIAL DISTANCE TO CLOSING SPRINGS
THETO   0.0000E+00   =ANGLE TO FIRST CLOSING SPRING
DTHET   0.0000E+00   =ANGLE BETWEEN SPRINGS,
RIEL(20) =INSIDE RADIUS OF ELEMENT
  2.090   2.090   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
ROEL(20) =OUTSIDE RADIUS OF ELEMENT
  2.112   2.647   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
ELEML(20) =ELEMENT LENGTH
  0.1250   0.7790   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
DENS(20) =ELEMENT DENSITY
  0.3280   0.3280   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
ZL(20) =AXIAL DIST. FROM INTERFACE TO ELEM.
  0.0000E+00 0.1250   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
  0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
*SPRING AND DAMPING
SPPRE =   0.0000E+00   SINGLE SPRING PRELOAD
NOSP   =   0.0000E+00   NUMBER OF SPRINGS
SKXX   =   4157.   FLUID-FILM STIFFNESS, KXX
SKXY   = -2356.   FLUID-FILM STIFFNESS, KXY
SKYX   =   0.0000E+00   FLUID-FILM STIFFNESS, KYX
SKYY   =   0.0000E+00   FLUID-FILM STIFFNESS, KYY
DXX   =   25.60   FLUID-FILM DAMPING
DXY   =   0.0000E+00   FLUID-FILM DAMPING
DYX   =   0.0000E+00   FLUID-FILM DAMPING
DYY   =   45.40   FLUID-FILM DAMPING
CO   =   0.3000E-02   RING SEAL CLEARANCE
HO   =   0.0000E+00   EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL   =   0.0000E+00   EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA =   186.4   SHAFT ROTATIONAL SPEED
POD   =   72.00   OD PRESSURE
PID   =   60.00   ID PRESSURE
COFSC =   0.7500E-01   COEFFICIENT OF FRICTION, SECONDARY SEAL
VISC   =   0.8125E-07   FLUID FILM VISCOSITY
DT   =   0.3371E-03   VALUE OF TIME STEP INCREMENT
NTS   =   1000.   NUMBER OF TIME STEPS
NT   =   1.000   INITIAL TIME STEP NUMBER

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*INITIAL CONDITIONS
XO   =   0.2400E-02   SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION
YO   =   0.2400E-02   SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION
ZO   =   0.0000E+00   SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION
AO   =   0.0000E+00   SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,R
AD.
BO   =   0.0000E+00   SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,R
AD.
OMEGAX = 186.4   SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS,
RAD/S
OMEGAY = 186.4   SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS,
RAD/S
OMEGAZ = 0.0000E+00 SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS
RAD/S
TINIT = 0.0000E+00 INITIAL TIME, SEC

     TOTAL MASS,LB.-SEC**2/IN = 0.5512104E-02

     CG DISTANCE,IN. =   0.5119731

     POLAR MOMENT OF INERTIA,LB-SEC**2-IN = 0.3131006E-01

     TRANSVERSE MOMENT OF INERTIA,LB.-SEC**2-IN = 0.1593852E-01

ACL=CLOSING AREA,IN**2= 0.2904214

FHCL=HYDRAULIC CLOSING FORCE,LBS.=   20.91034

AIF=INTERFACE AREA,IN**2,= 0.2904214

FIFPRE=INTERFACE PRELOAD,LBS=   20.91034

SCFRIC=SECONDARY SEAL PRELOAD FRICTION,LBS=   1.568276

HO=INITIAL FILM THICKNESS OR INTERFERENCE,IN.= -0.2169600E-05

LIST CONTIN   TO CONTINUE THIS CASE READ THE FOLLOWING   VARIABLES IN NAME

NT= 1001

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Figure 51. Kirk's Figure 7 DYSEAL Output (mil)

```
U(1)=  0.1720766E-03      U(2)= -0.2681162E-03      U(3)=  0.0000000E+00
U(4)=  0.0000000E+00      U(5)=  0.0000000E+00
UDOT(1)=  0.2760304E-01   UDOT(2)=  0.2964780
UDOT(3)=  0.0000000E+00   UDOT(4)=  0.0000000E+00
UDOT(5)=  0.0000000E+00
UDOTT(1)=   259.7914      UDOTT(2)=  -1.751540
UDOTT(3)=  0.0000000E+00  UDOTT(4)=  0.0000000E+00
UDOTT(5)=  0.0000000E+00
FRICX=   1.568276         FRICY=  -1.568276
FRICZ=  0.0000000E+00     FRICA= -0.8029148
FRICB= -0.8029148
```

Figure 51. Continued

95TM1
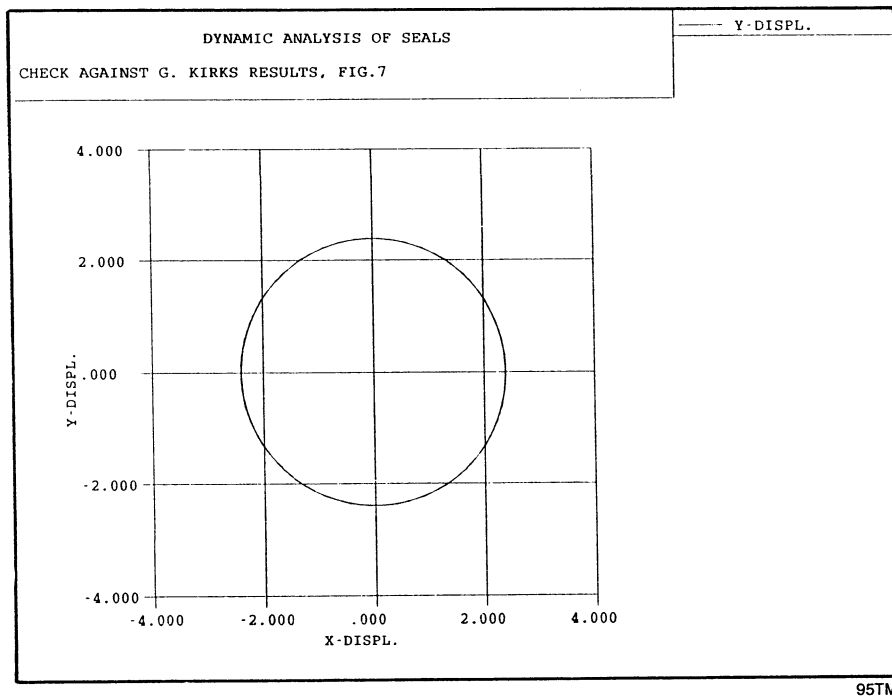
Figure 52. Kirk's Figure 7 Rotor Orbit (mil)
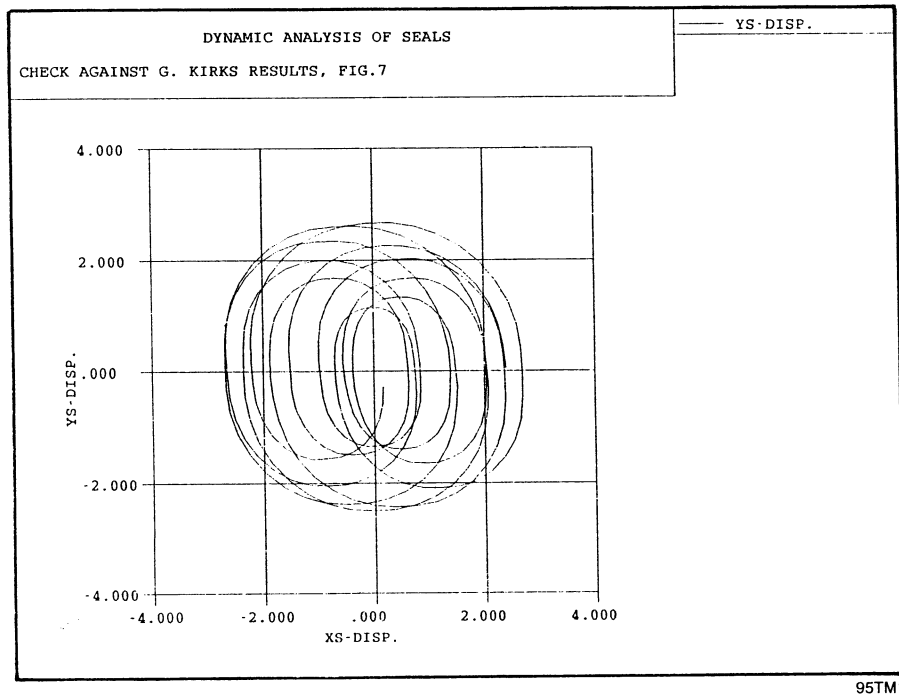
Figure 53. Kirk's Figure 7 DYSEAL Seal Ring Orbit (mil)
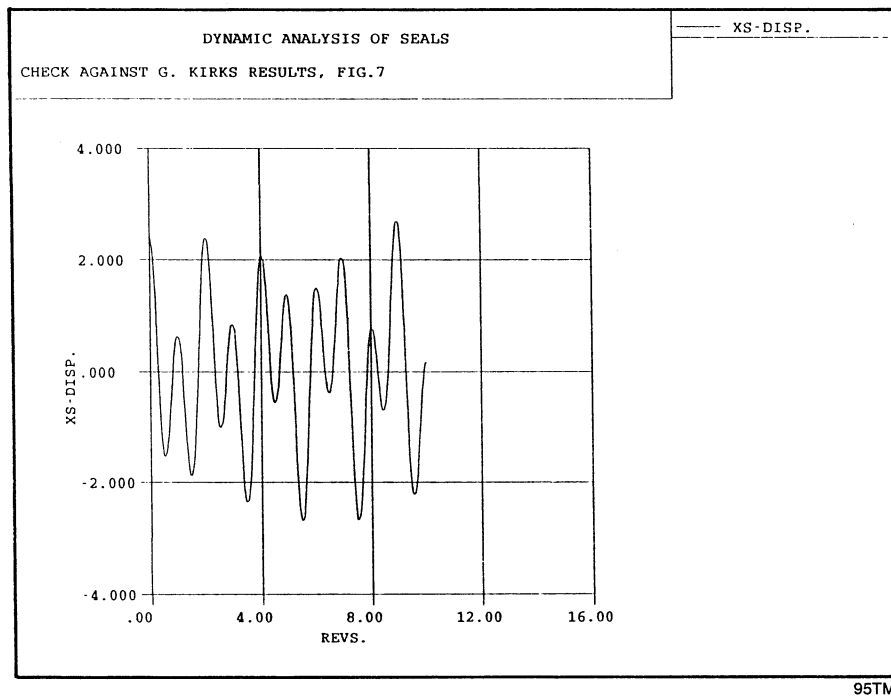
Figure 54. Kirk's Figure 7 DYSEAL x Displacement (mil)
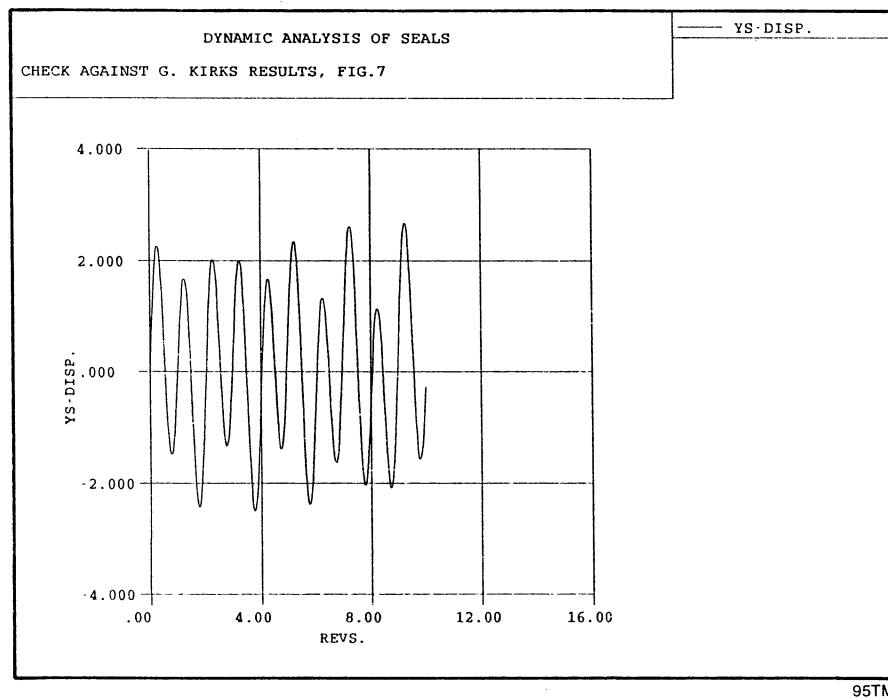
Figure 55. Kirk's Figure 7 DYSEAL y Displacement (mil)
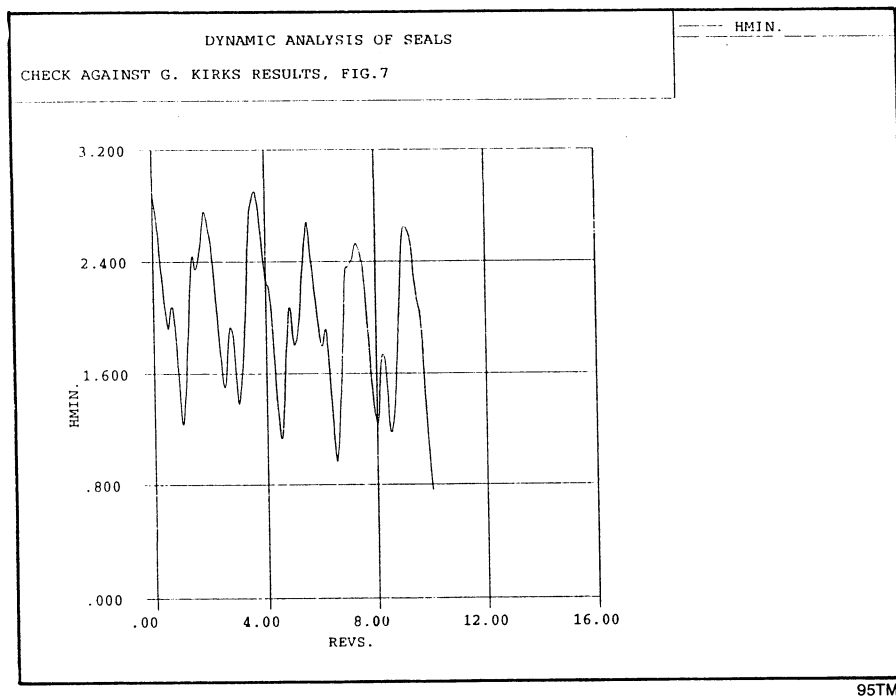
Figure 56. Kirk's Figure 7 DYSEAL Minimum Film Thickness (mil)
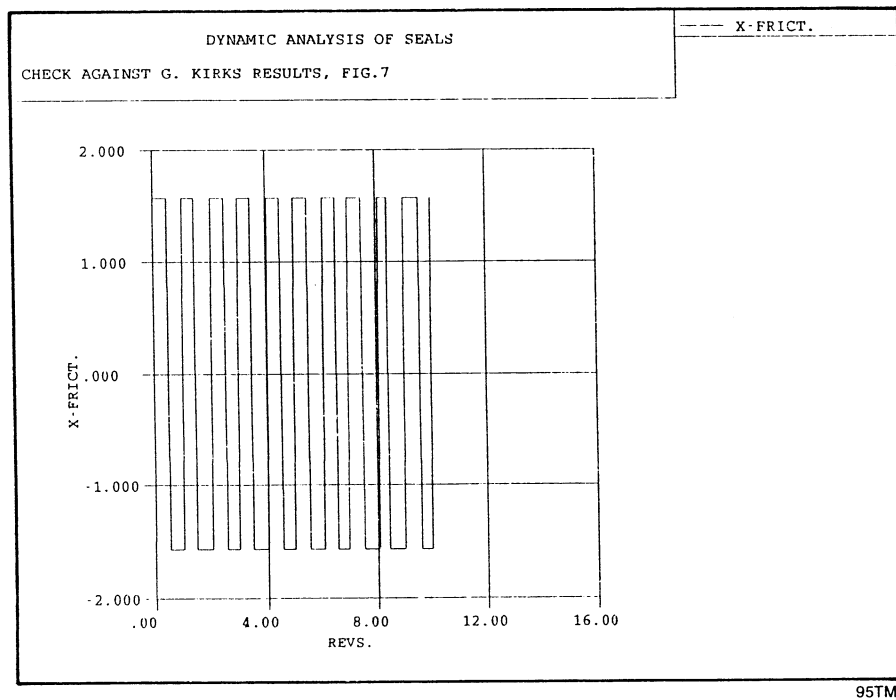
Figure 57. Kirk's Figure 7 DYSEAL x Friction (lb)
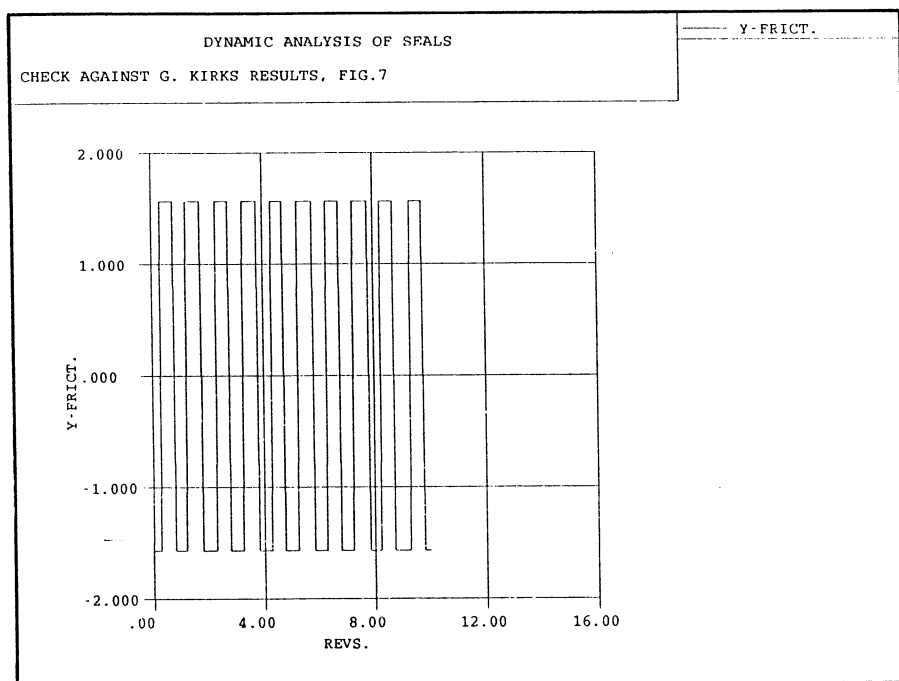
Figure 58. Kirk's Figure 7 DYSEAL y Friction (lb)

Rotor Transient   Rotor Relative to Seal

Clearance Circle

Seal Ring Transient

814.0			86.1		
WJ	= 200.00		N	= 1780.0
H/V	= 0.00		EMU	= 0.800
WSR	= 2.13		RJ	= 2.090
CR	= 0.0030		L	= 0.600
Viscosity	= 0.8125E-07		Mu-F	= 0.150
F-A	= 20.9000		P-L	= 60.00
P-H	= 72.00		TMAX	= 6.280
P-C	= -14.70		TH-N	= 36
H	= 0.03140			
NZ	= 6			

WJ	=	Modal mass of rotor shaft (lb_m)
N	=	Rotor shaft speed (rpm)
H/V	=	Horizontal or vertical indicator (1 ≡ horizontal; 0 ≡ vertical)
EMU	=	Rotor shaft modal mass eccentricity relative to seal clearance (DIM)
WSR	=	Seal ring mass (lb_m)
RJ	=	Seal journal radius (in.)
CR	=	Seal radial clearance (in.)
L	=	Seal axial length (in.)
Viscosity	=	Absolute viscosity of sealing fluid (lb-sec/in.^{2})
Mu-F	=	Face friction factor (DIM)
P-H	=	Seal high pressure (lb/in.^{2})
P-L	=	Seal low pressure (lb/in.^{2})
P-C	=	Seal liquid cavitation pressure (lb/in.^{2})
H	=	Time step for transient simulation (rad)
TMAX	=	Maximum time for each segment of response (rad)
NZ	=	Axial grid points for pressure profile
TH-N	=	Pressure profile grid points around circumference of seal

95TM1

Figure 59. Pump Seal Transient for a Reduced-Length Seal Showing Seal Ring
Tracking Rotor at an Eccentricity of ε = 0.75 (N = 1780 rpm = 29.7 Hz)

```
KIRK8
CHECK AGAINST G. KIRKS RESULTS, FIG.8
*
*HELP
*GEOMETRY
RING
EMOD        30.0E06
ROS         2.112
RIS         2.090
RSC         2.090
RSP         2.3
NELM        2
ZSPO        0.6
THETO       0.0
DTHET       0.0
RIEL(20)    2.090 2.090
ROEL(20)    2.112 2.647
ELEML(20)   .125 .475
DENS(20)    0.536 0.536
ZL(20)      0.0 .125
*SPRING AND DAMPING
SPPRE       0.
NOSP        0.0
SKXX        0.0
SKXY        9068.
SKYY        0.
SKYX        -1747.
DXX         18.9
DYX         0.
DYY         0.
CO          107.
HO          -.003
FFL         0.0
*OPERATING CONDITIONS
OMEGA       186.4
POD         72.
PID         60.
COFSC       0.075
VISC        0.8125E-07
DT          3.3708E-04
* CONTINUATION 1
NTS         1000
NT          1
*INITIAL CONDITIONS
XO          .0024
YO          .0024
ZO          .000
AO          .00000
BO          .00000
OMEGAX      186.4
OMEGAY      186.4
OMEGAZ      0.
TINIT       0.0
END
```

Figure 60. Kirk's Figure 8 DYSEAL Input

95TM1

1

ECHO OF INPUT

CHECK AGAINST G. KIRKS RESULTS, FIG.8

```
*HELP
*GEOMETRY
RING              T = TRUE FOR A RING SEAL
EMOD      0.3000E+08  =ELASTIC MODULUS OF RING SEAL
ROS       2.112       =OUTSIDE RADIUS OF RING SEAL
RIS       2.090       =INSIDE RADIUS OF SEAL INTERFACE
RSC       2.090       =O-RING SECONDARY SEAL INTERFACE
RSP       2.300       =MEAN SPRING RADIUS
NELM      2.000       =NUMBER OF GEOMETRICAL ELEMENTS
ZSPO      0.6000      =AXIAL DISTANCE TO CLOSING SPRINGS
THETO     0.0000E+00  =ANGLE TO FIRST CLOSING SPRING
DTHET     0.0000E+00  =ANGLE BETWEEN SPRINGS,
RIEL(20) =INSIDE RADIUS OF ELEMENT
  2.090     2.090     0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
ROEL(20) =OUTSIDE RADIUS OF ELEMENT
  2.112     2.647     0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
ELEML(20) =ELEMENT LENGTH
  0.1250    0.4750     0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
DENS(20) =ELEMENT DENSITY
  0.5360    0.5360     0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
ZL(20)  =AXIAL DIST. FROM INTERFACE TO ELEM.
  0.0000E+00  0.1250  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
*SPRING AND DAMPING
SPPRE     0.0000E+00   SINGLE SPRING PRELOAD
NOSP      0.0000E+00   NUMBER OF SPRINGS
SKXX      9068.        FLUID-FILM STIFFNESS, KXX
SKXY      0.0000E+00   FLUID-FILM STIFFNESS, KXY
SKYY     -1747.        FLUID-FILM STIFFNESS, KYY
SKYX      18.90        FLUID-FILM STIFFNESS, KYX
DXX       0.0000E+00   FLUID-FILM DAMPING
DYX       0.0000E+00   FLUID-FILM DAMPING
DXY       0.0000E+00   FLUID-FILM DAMPING
DYY       107.0        FLUID-FILM DAMPING
CO        0.3000E-02   RING SEAL CLEARANCE
HO        0.0000E+00   EQUILIBRIUM FILM THICKNESS FOR FACE SEALS
FFL       0.0000E+00   EQUILIBRIUM FLUID-FILM FORCE
*OPERATING CONDITIONS
OMEGA  =  186.4        SHAFT ROTATIONAL SPEED

POO    =  72.00        OD PRESSURE

PID    =  60.00        ID PRESSURE

COFSC  =  0.7500E-01   COEFFICIENT OF FRICTION,SECONDARY SEAL
```

```
VISC   =  0.8125E-07   FLUID FILM VISCOSITY

DT     =  0.3371E-03   VALUE OF TIME STEP INCREMENT

* CONTINUATION 1
NTS    =  1000.        NUMBER OF TIME STEPS

NT     =  1.000        INITIAL TIME STEP NUMBER

*INITIAL CONDITIONS
XO     =  0.2400E-02   SHAFT VIBRATION AMPLITUDE IN THE X DIRECTION

YO     =  0.2400E-02   SHAFT VIBRATION AMPLITUDE IN THE Y DIRECTION

ZO     =  0.0000E+00   SHAFT VIBRATION AMPLITUDE IN THE Z DIRECTION

AO     =  0.0000E+00   SHAFT VIBRATION AMPLITUDE ABOUT THE Y-Y AXIS,R
AD.
BO     =  0.0000E+00   SHAFT VIBRATION AMPLITUDE ABOUT THE X-X AXIS,R
AD.
OMEGAX =  186.4        SHAFT VIBRATION FREQUENCY ALONG THE X-X AXIS,
RAD/S
OMEGAY =  186.4        SHAFT VIBRATION FREQUENCY ALONG THE Y-Y AXIS,
RAD/S
OMEGAZ =  0.0000E+00   SHAFT VIBRATION FREQUENCY ALONG THE Z-Z AXIS,
RAD/S
TINIT  =  0.0000E+00   INITIAL TIME, SEC

          TOTAL MASS,LB.-SEC**2/IN  =  0.5512082E-02

          CG DISTANCE,IN.  =     0.3597592

          POLAR MOMENT OF INERTIA,LB-SEC**2-IN =  0.3128505E-01

          TRANSVERSE MOMENT OF INERTIA,LB.-SEC**2-IN =  0.1574978E-01


ACL=CLOSING AREA,IN**2=  0.2904214

FHCL=HYDRAULIC CLOSING FORCE,LBS.=    20.91034

AIF=INTERFACE AREA,IN**2,=  0.2904214

FIFPRE=INTERFACE PRELOAD,LBS=     20.91034

SCFRIC=SECONDARY SEAL PRELOAD FRICTION,LBS=    1.568276

HO=INITIAL FILM THICKNESS OR INTERFERENCE,IN.= -0.1440000E-05
```

Figure 61. Kirk's Figure 8 DYSEAL Output

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LIST CONTIN

TO CONTINUE THIS CASE READ THE FOLLOWING   VARIABLES IN NAME

```
NT=   1001
U(1)= -0.2499731E-04     U(2)=  0.6461446E-04     U(3)=  0.0000000E+00
U(4)=  0.0000000E+00     U(5)=  0.0000000E+00
UDOT(1)= -0.8953734E-01  UDOT(2)=  0.4021290
UDOT(3)=  0.0000000E+00  UDOT(4)=  0.0000000E+00
UDOT(5)=  0.0000000E+00
UDOTT(1)=  -58.74976     UDOTT(2)=   5.198731
UDOTT(3)=  0.0000000E+00 UDOTT(4)=  0.0000000E+00
UDOTT(5)=  0.0000000E+00
FRICX=   1.568276        FRICY=  -1.568276
FRICZ=  0.0000000E+00    FRICA=  -0.5642016
FRICB= -0.5642016
```

....
....
....

Figure 61. Continued
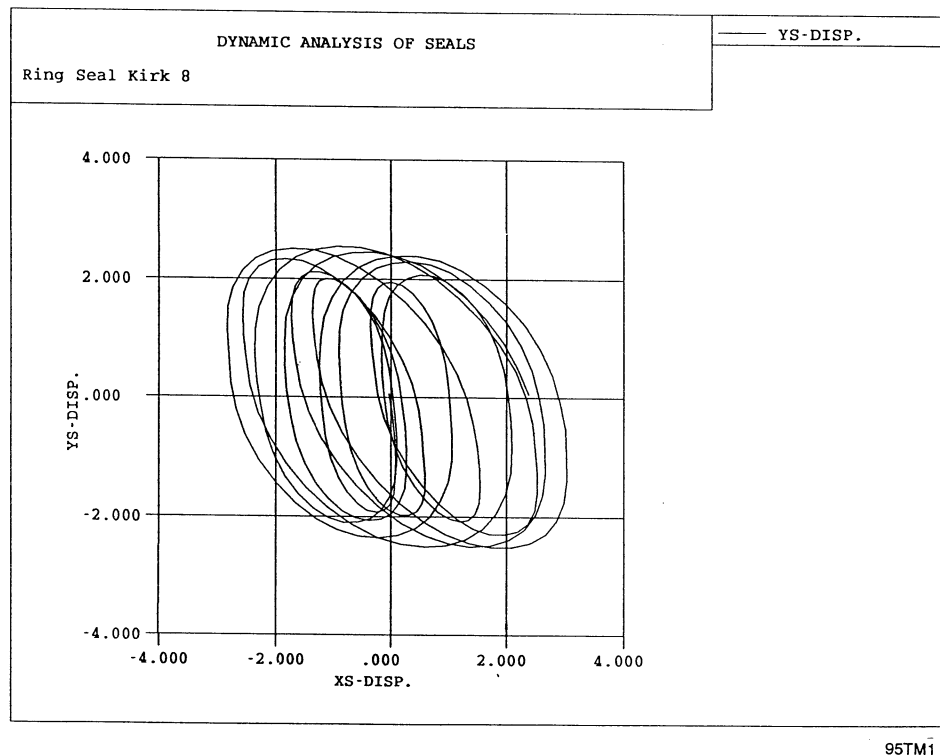
Figure 62. Kirk's Figure 8 DYSEAL Seal Ring Orbit (mil)
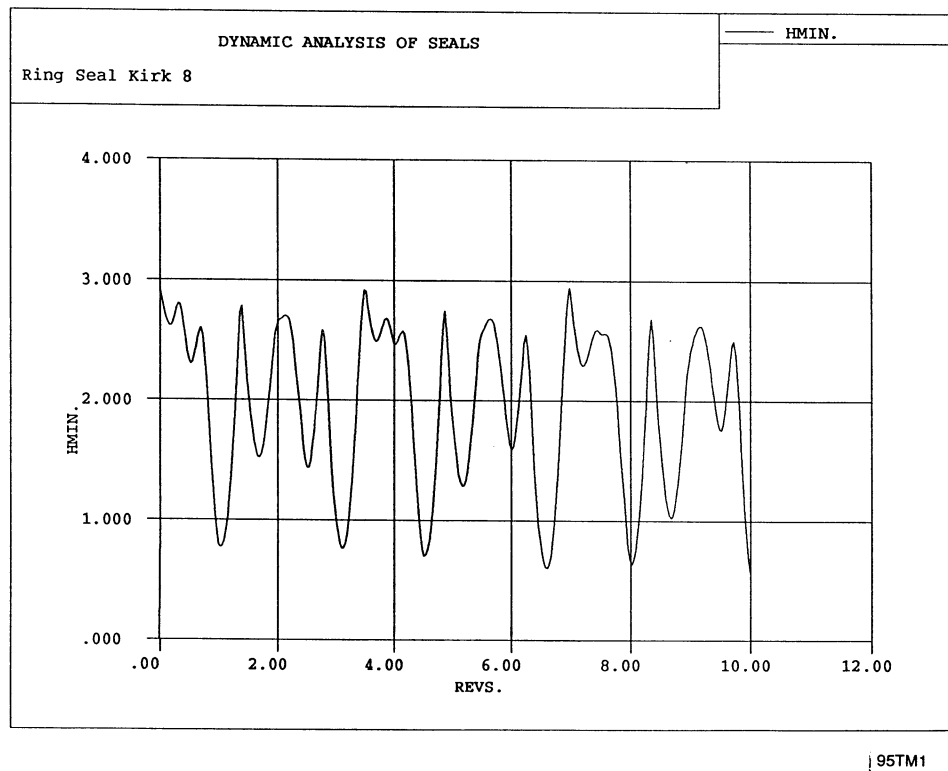
Figure 63. Kirk's Figure 8 DYSEAL Minimum Film Thickness (mil)

5.0 VERIFICATION

Several methods of verification were accomplished. Internal checks were made against closed-form solutions. Some mass, spring, and damper vibration problems were examined and compared against closed-form solutions. Also, comparisons were made against experimental data available in the literature. Ring seal verification was presented in the preceding section.

5.1 Internal Checks

An example of internal checks of the code is evaluation of spring forces and moments. The numerical approach used in the code can be compared against a closed-form solution. For the ith spring, the moment is

$$\overline{M}_s^i = \overline{r}_{sp}^i \times \overline{F}_s^i = \left(z_{sp} - z_{cg}\right)\hat{k} + \left(R_{sp}\cos\theta_i\hat{i} + R_{sp}\sin\theta_i\hat{j}\right) \times \left(-k_s z_i\hat{k}\right) \tag{5.1}$$

where:

> $\overline{M}_s^i$ = moment from ith spring located at θ_i
> $\overline{F}_s^i$ = force from ith spring
> z_{sp} = z distance to ith spring
> R_{sp} = spring radius
> θ_i = angular coordinate to ith spring
> z_i = displacement of ith spring in z direction
> z_{cg} = z distance to CG

The seal ring motion in the z direction, z_i, is given by

$$z_i = z_s + R_{sp}\left(\beta_s\sin\theta_i - \alpha_s\cos\theta_i\right) \tag{5.2}$$

where the variables have been previously defined.

After substituting Equation (5.2) into Equation (5.1), expanding and summing over all springs, the following equation results:

$$\overline{M}_s = \left(R_{sp}k_s z_s \sum\cos\theta_i + R_{sp}^2 k_s\beta_s \sum\sin\theta_i\cos\theta_i - R_{sp}^2 k_s\alpha_s \sum\cos^2\theta_i\right)\hat{j}$$
$$- \left(R_{sp}^2 k_s z_s \sum\sin\theta_i + R_{sp}^2 k_s\beta_s \sum\sin^2\theta_i - R_{sp}^2 k_s\alpha_s \sum\sin\theta_i\cos\theta_i\right)\hat{i} \tag{5.3}$$

where the $\hat{j}$ component equals the moment about the y axis and the $\hat{i}$ component equals the moment about the x axis.

Consider six springs with the first spring starting at an angle of 10°. The summation coefficients are indicated on Table 3.

Table 3. Summation Coefficients

$$K_{sp} = 2;\ N_{sp} = 6;\ k = 100\ lb/in.$$

θ	sinθ	cosθ	sinθ cosθ	sin²	cos²
10	0.1736	0.9848		0.0301	0.9698
70	0.9397	0.342		0.883	0.117
130	0.7660	-0.6428		0.5866	0.4132
190	-0.1736	-0.9848		-0.301	0.9698
250	-0.9397	-0.342		0.883	0.117
310	-0.7660	0.64281		0.5868	0.4132
Σ	0	0	0	3.0	3.0

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Referring to Equation (5.3),

$$K_{x\alpha} = R_{sp}k_s \sum \cos\theta = 0$$

$$K_{\beta\alpha} = R_{sp}^2 k_s \sum \sin\theta\cos\theta = 0$$

$$K_{\alpha\alpha} = R_{sp}^2 k_s \sum \cos^2\theta = 2^2(100)(3) = 1200 \text{ lb / in.}$$

Similarly,

$$K_{z\beta} = K_{\alpha\beta} = 0, \ K_{\beta\beta} = 1200$$

Also, the axial stiffness = $6 \times 100 = 600$ lb/in. The spring stiffness matrix as computed by the program is as follows:

```
SKSP(I,J) =
0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
0.00000E+00   0.00000E+00   600.00         0.00000E+00   0.00000E+00
0.00000E+00   0.00000E+00  -0.22204E-13   1200.0        -0.33307E-12
0.00000E+00   0.00000E+00   0.17764E-12  -0.28866E-12    1200.0
SPF(I) =
0.00000E+00   0.00000E+00   0.00000E+00
```

This checks precisely with the closed-form solutions. Similar results were obtained for varying the number of springs and the independent stiffness values.

5.2 Mass, Spring, Damper Vibrations

Several mass, spring, and damper vibration problems can be used to check out portions of the code. First, consider a forced vibration problem, as depicted in Figure 64. The base represents the shaft; the mass represents the seal ring. The base is the source of excitation, and the response of the seal ring or mass, M, is desired. The initial parameters tested were:

k = 10,000 lb/in.
ℓ = 10 lb-sec/in.
M = 10 lb = 10/386.4 = 0.02588 lb-sec²/in.
X = 0.002 in.
ω = 1000 rad/sec
C = 10 lb-sec/in.

As derived from Thomson [4], the maximum relative displacement, Z, (= y - x) is given by

$$Z = \frac{m\omega^2 X}{\sqrt{\left(k - m\omega^2\right)^2 + (C\omega)^2}} = \frac{(0.02588)(1000)^2(0.002)}{\sqrt{\left(10,000 - 0.0259(1000)^2\right)^2 + \left(10(1000)\right)^2}} \tag{5.4}$$

$$= 0.002758 \text{ in.} = 2.758 \text{ mil}$$

Z represents the maximum difference between the amplitude of the mass, y, and the excitation, X. As shown on the computer output graph (Figure 65), the measured difference equals 2.74 mil. The phase angle as a function of frequency and damping is shown on Figure 66.

$$\frac{\omega}{\omega_n} = \frac{\omega}{\sqrt{\frac{k}{m}}} = \frac{1000}{\sqrt{\frac{10,000}{0.0258}}} = 1.6 \tag{5.5}$$

$$\rho = \frac{C}{C_c} = \frac{C}{2m\omega_n} = \frac{10}{2(0.02588)(622)} = 0.3106 \tag{5.5}$$

From Figure 66, the phase angle, ϕ, is approximately 135°. The computed value is estimated to be 136° as measured from the output curves of Figure 65. Considering graphical interpretations, the corroboration is excellent. Similar results were obtained using the ring seal option of the code exciting the shaft in the x direction, as shown on Figure 67.

5.3 Verification Against Data in the Literature

Di Russso [5] did extensive dynamic testing of spiral-groove seals. The seals were subjected to constant load rotation, with installation runout of the seal seat (rotating member) and then to constant load rotation with installation runout plus an axial excitation of 50 μm (2 mil) at 100-Hz frequency. Figure 68 schematically shows the seal seat vibrational modes. The installation misalignment of the seal seat was approximately 35 μrad about both the x and y axes. Tests were run with and without secondary seals.

Figure 69 shows response of the seal at 14,000 rpm without a secondary seal in place. The film thickness frequency is approximately 6 times synchronous for the 14,000-rpm case. The case was simulated by determining the stiffness and damping characteristics of the spiral groove and establishing the physical characteristics of the seal ring. The input for the DYSEAL run is shown in Figure 70. The minimum film thickness in mils versus shaft revolutions, computed by the code is shown in Figure 71. The 6 per rev frequency is shown in Figure 72. The results are nearly identical to the steady mode without the axial excitation. The implication is that the seal ring tracks the exciting shaft perfectly. The input for the computer studies is identical to Figure 70, except that Z0 is give a value of 0.002. Computer results of film thickness are shown in Figure 73. The film thickness shows a definite trace of the excitation frequency. A blown-up view of the film thickness is shown in Figure 74, and the six times synchronous frequency is clearly discernible. The axial displacement of the seal seat (ZS) and seal ring (Z) are shown in Figure 75. They are in unison, confirming the tracking capability of the seal as experienced on test. The variations indicated by the film thickness curves do not show in the axial mode but are indicated by the rotational response about the x and y axes. Figure 76 shows the rotational response about the x axis superimposed on the pure sinusoidal excitation. The jogged sine curve provides the differences between excitation and response. In general, the computational results agree very favorably with the experimental data.
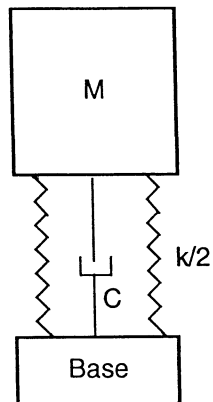
Figure 64. Mass, Spring, and
Damper System
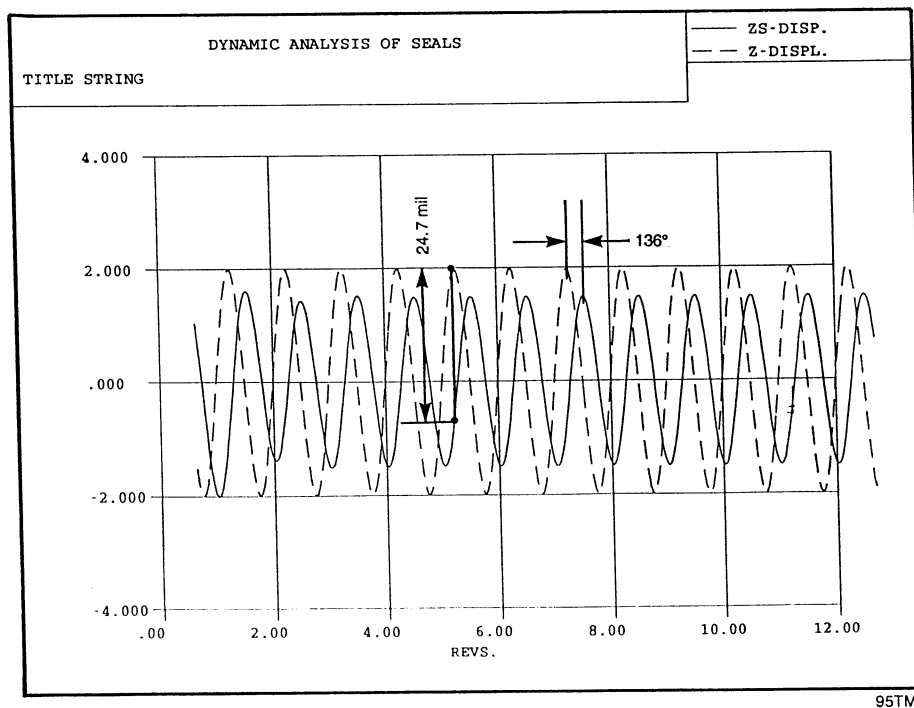
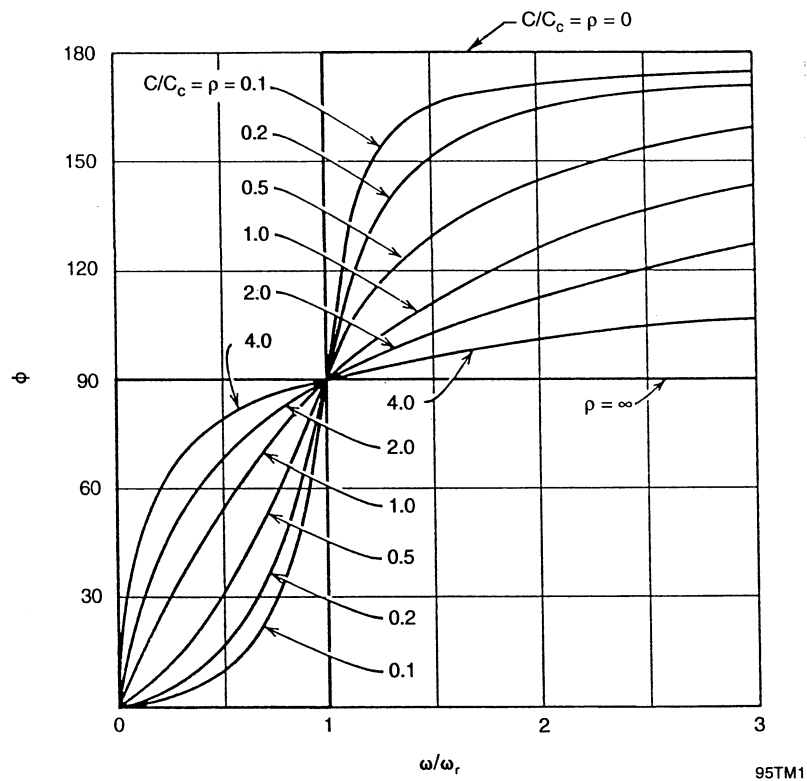Figure 65. Single-Degree-of-Freedom Forced Vibration

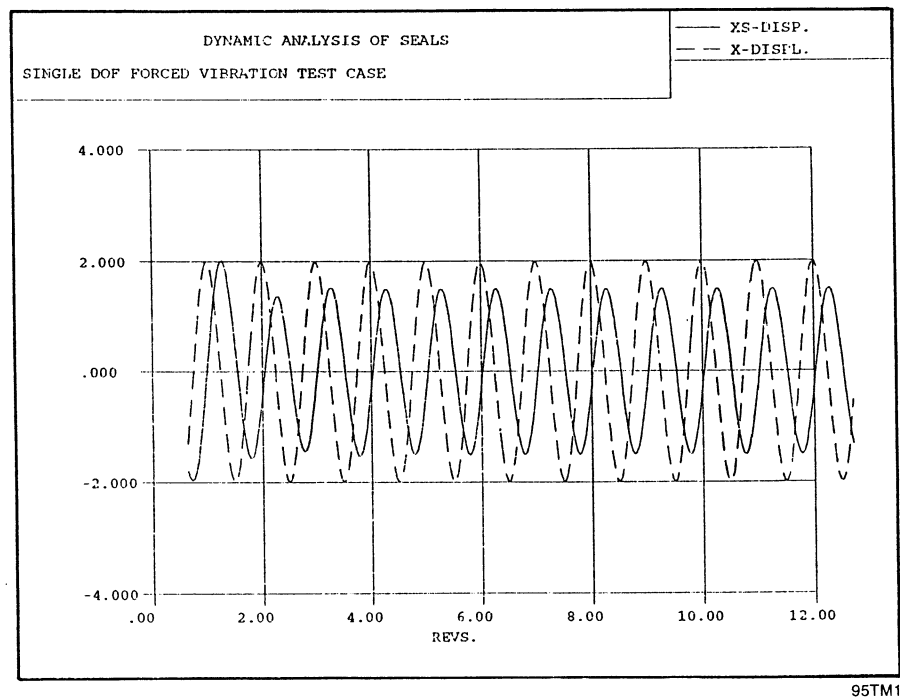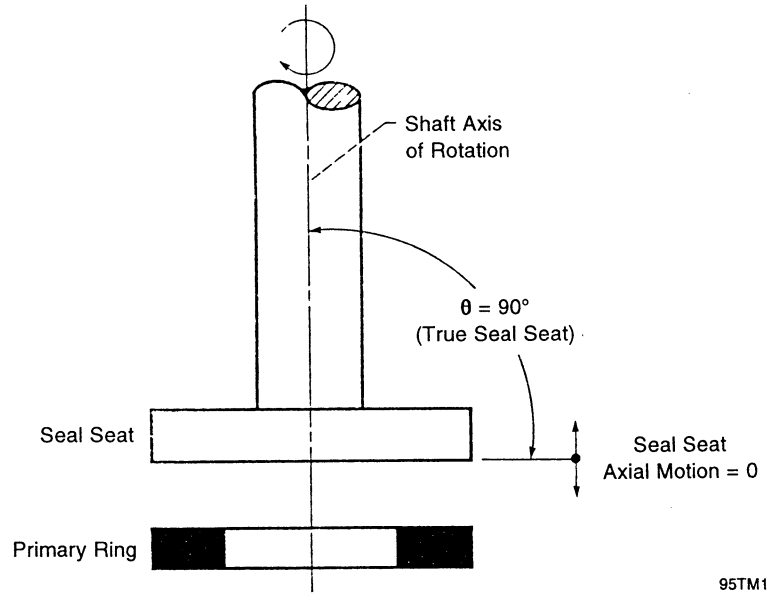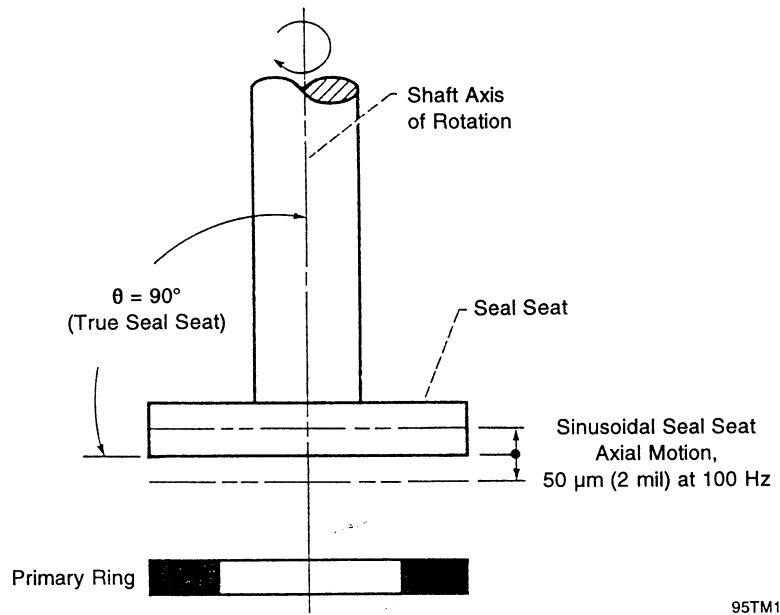Figure 66. Phase Angle as a Function of Damping and Frequency

Figure 67. Ring Seal Option: Single-Degree-of-Freedom Forced Vibration Problem

Shaft Axis of Rotation

$\theta = 90°$
(True Seal Seat)

Seal Seat

Seal Seat
Axial Motion = 0

Primary Ring

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a) Steady Seal Seat Mode with True Seal Seat

Shaft Axis of Rotation

$\theta = 90°$
(True Seal Seat)

Seal Seat

Sinusoidal Seal Seat
Axial Motion,
50 μm (2 mil) at 100 Hz

Primary Ring

95TM1

b) Sinusoidal Seal Seat Mode with True Seal Seat

Figure 68. Schematic Showing Seal Seat Vibrational Modes
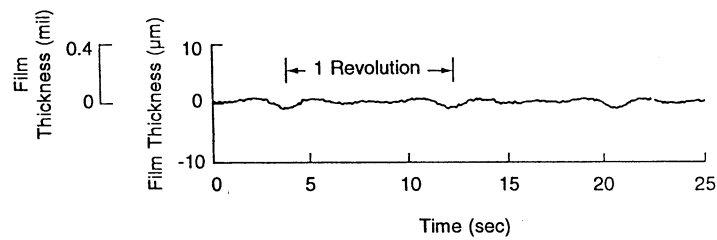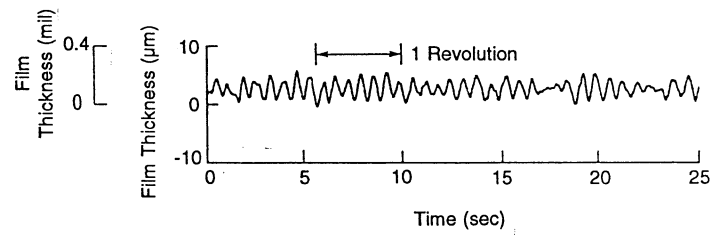
Figure 69. Film Thickness as a Function of Time (Probe 1) for Inward-Pumping
Spiral-Groove Seal (No Secondary Seal) and Steady Seal Seat Mode

```
DIRUSS2A
14000 RPM ALIGNED, NO AXIAL EXCITATION, 35 MICRO-RADIANS MISALIGNMENT
*
HELP
*GEOMETRY
PISTON
ZSCO       0.6
ROS        1.850
RIS        1.608
RSCI       1.65
RSCO       1.71
RSP        1.80
NELM       5
ZSPO       0.35
THETO      0.0
DTHET      .5236
RIEL(20)   1.545  1.845  1.945  1.390 1.390
ROEL(20)   1.845  1.945  2.005  1.945 1.510
ELEML(20)  0.25  0.200  0.300  0.08 0.46
DENS(20)   0.0361 0.284  .450   0.45 0.45
ZL(20)     0.0 .05  0.08  0.29 0.38
APR        .633
WPR        .060
*SPRING AND DAMPING
SPPRE      0.0
NOSP       12
SKZZ       178520.
SKZA       0.0
SKZB       0.0
SKBZ       0.0
SKBB       256580.
SKBA       9288.
SKAZ       0.0
SKAB       -9288.
SKAA       256580.
DZZ        0.4
DZB        0.0
DZA        0.0
DBZ        0.0
DBB        0.8
DBA        0.0
DAZ        0.0
DAB        0.0
DAA        0.8
SPRST      5.583
HO         .00018
FFL        16.4
*OPERATING CONDITIONS
OMEGA      1466.0766
POO        7.4575
PID        0.0
COFSC      0.0
VISC       2.63E-09
DT         85.71875E-06
NTS        1000
NT         1
*INITIAL CONDITIONS
XO         .000
YO         .000
ZO         .000
AO         0.000035
BO         0.000035
OMEGAX     0.
OMEGAY     0.
OMEGAZ     628.32
TINIT      0.0
```

```
OMEGAB     1466.0766
OMEGAA     1466.0766
END
```

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Figure 70. Input for Spiral-Groove Seal; 14,000 rpm, No Axial Excitation
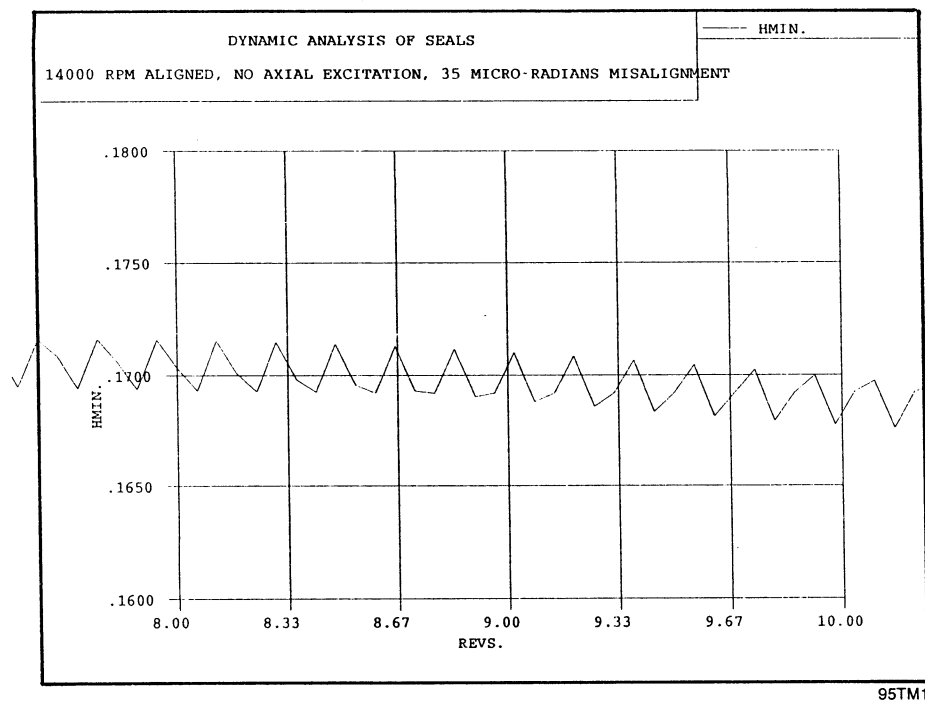
Figure 71. Results of DYSEAL Analysis; Film Thickness versus
Revolutions (Steady Seal Seat Mode)
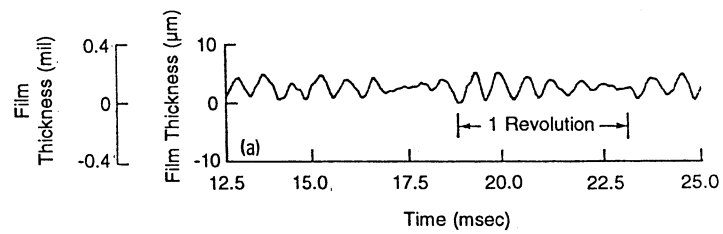
a) Steady Seal Seat Mode
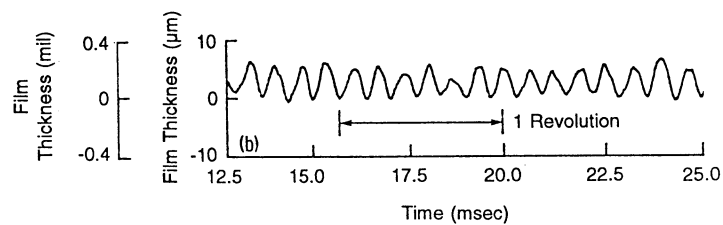
b) Sinusoidal Seal Seat Mode; Amplitude = 50 μm (2 mil);
Frequency = 100 Hz

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Figure 72. Film Thickness; Sinusoidal Axial Vibration
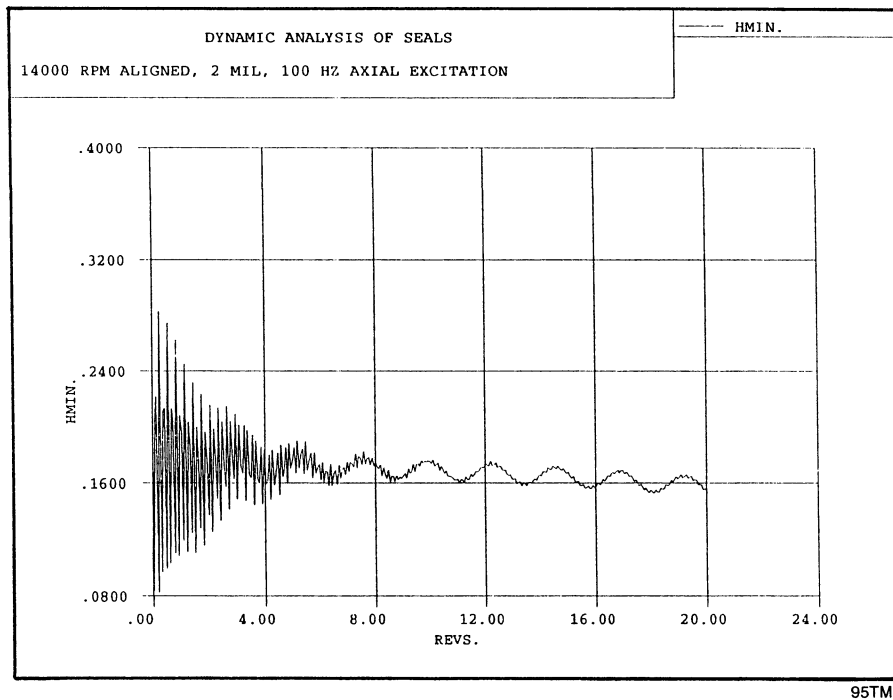
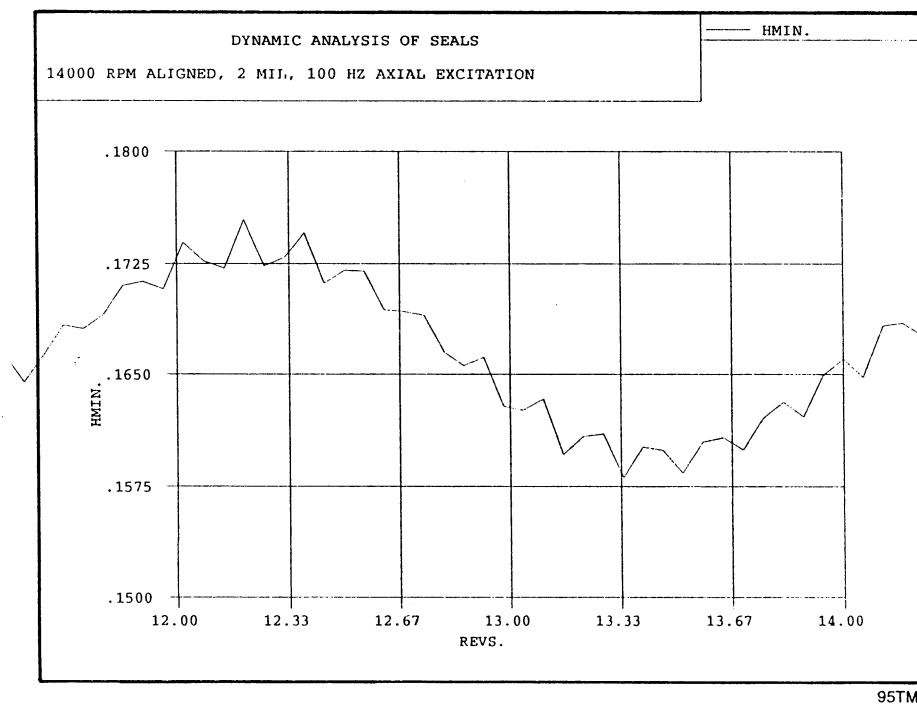Figure 73. DYSEAL Film Thickness; Sinusoidal Axial Vibration

Figure 74. DYSEAL Magnified View of Film Thickness;
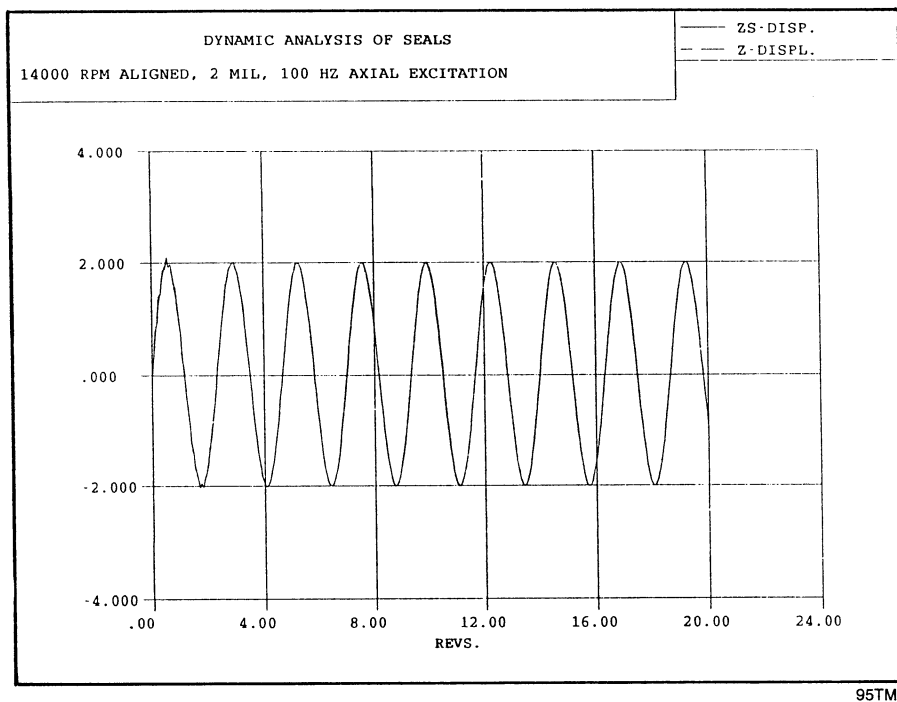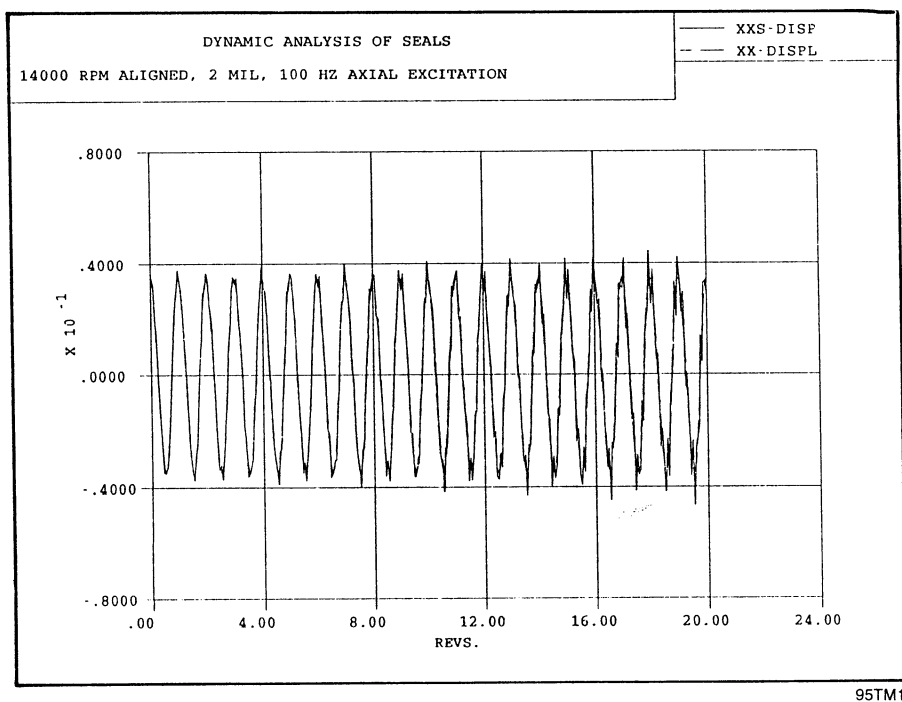Sinusoidal Axial Vibration

Figure 75. Axial Motion of Shaft and Seal

Figure 76. Rotational Response About x Axis for Axial Sinusoidal Excitation

6.O OPERATING ENVIRONMENT

The DYSEAL code has been produced with a WATCOM compiler under an OS/2 operating system. An extension to FORTRAN 77 is the use of an include file DYCOM. Include files are supported by most FORTRAN compilers in use today. Users with compilers that do not support an include statement can replace this statement with the entire DYCOM file. The executable file of the program takes 203,489 bytes.

7.O REFERENCES

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3. "Transient Response of Floating-Ring Liquid Seals." Transactions of ASME, *Journal of Tribology*, Vol. 110, pp. 572-578 (July 1988).

4. Thomson, W.T. "Mechanical Vibrations." Prentice Hall, Copyright 1948.

5. DiRusso, E. "Dynamic Response of Film Thickness in Spiral-Groove Face Seals." NASA Technical Paper 2544, December 1985.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The computer code described in this manual can determine the tracking capability of fluid film seals and can be used for parametric geometric variations to find acceptable configurations. The type of seals that can be analyzed are: 1) fluid film face seals with secondary piston ring seals, and 2) floating ring seals. For the first type of seal, the shaft or rotor can be given five degrees of freedom, consisting of three translations (x, y, and z) and two rotations about the x and y axes, respectively. The seal ring response is also in five degrees of freedom. The interface is represented by cross coupled stiffness and damping coefficients that are obtained from other codes. The effects of Coulomb friction of the secondary seals on seal ring response are included. The analysis of the floating ring seal permits two degrees of freedom for both the shaft and ring, and is intended to determine seal ring response to an orbiting shaft. The method of computation is a forward integration in time that provides absolute motions in all degrees of freedom. This users' manual documents the theory used, describes input and output parameters, and provides sample problems and code verification.

14. SUBJECT TERMS

Seals; Dynamic response; Face seal; Ring seal; Fluid film seal; Coulomb friction; Users' manual

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